SUMMARY OF DISCIPLINE PANEL REVIEWS OF THE REQUEST FOR INFORMATION (RFI) RESPONSES CONCERNING MISSION CONCEPTS IN THE POST-2002 ERA

Research Division
Office of Earth Science
NASA Headquarters

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SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

ATMOSPHERIC CLIMATE PHYSICS

Summary of Step 1 Mission Concept Reviews July 1998

SCIENCE-BASED PRIORITIES FOR EOS POST-2002 FLIGHT MISSIONS
ATMOSPHERIC CLIMATE PHYSICS

Atmospheric Climate Physics Panel - Overall Science Priority

Summaries of the four mission concepts considered by the Atmospheric Climate Physics Panel are presented here in order of their scientific priority. The two highest priority mission concepts are research missions needed to make progress in understanding radiative forcing and feedback processes which have significant impact on the Earth's climate. The two lower priority mission concepts are monitoring missions for the continued systematic measurement of Earth system state variables and solar forcing. The state variables, in a sense are the system response to forcing and feedbacks. The following table outlines the science priority, question addressed, and priority reasoning for the four concept missions:

Priority	Science Question	Mission Type	Priority Justification
1	Radiation Forcing by Aerosols	Research	Of all of the radiative forcing processes affecting climate, aerosols have the largest uncertainty in the magnitude of their contribution and their spatial and temporal dependence. Global measurements of aerosol optical properties require an extraordinary complement of dedicated space-borne remote sensing instruments
2	Radiation Feedback by Clouds	Research	The magnitude of cloud radiative forcing of climate is second only to water vapor. Dramatic changes in cloud radiative feedback are governed by subtle changes in the environment including aerosols. A dedicated space-borne mission including active and passive sensors is required.
3	Variability and Trends in Basic Climate Variables	Monitoring	During the period of time following EOS PM-1 and NPOESS, a continuation of space-borne measurements of atmospheric temperature, moisture and TOA radiation fluxes is required
4	Variability in Solar Radiative Forcing	Monitoring	During the period of time following TSIM and NPOESS, a continuation of space-borne measurements of solar irradiance is required

1. First Science Question: Radiation Forcing of Climate by Aerosols

Arguably the most pressing scientific issue presently identified for climate change studies is the unknown radiative forcing caused by atmospheric aerosols. Natural variations of aerosols, especially due to episodic eruptions of large volcanoes, are recognized as a significant climate forcing, that is, a factor that alters the planetary radiation balance and thus may cause a global temperature change. In addition, there are several ways in which human activities are altering the amount and geographic distribution of atmospheric aerosols, and thus possibly affecting climate. Climate forcing due to changing aerosol concentration and properties, include both the direct radiative forcing by aerosols and the indirect radiative forcing caused by effects of changing aerosols on cloud properties. These climate forcings due to changes of aerosols are not determined well, especially in the case of aerosols produced through human activity. Indeed, aerosols are one of the greatest sources of uncertainty in interpretation of climate change of the past century and in projection of future climate change.

The large uncertainty that aerosols introduce in our understanding of climate change is illustrated by the Intergovernmental Panel on Climate Change published in Climate Change 1994: Radiative Forcing of Climate Change. Furthermore, the National Research Council has recommended a research plan in its Aerosol Radiative Forcing and Climate Change which also contains background material that is useful in establishing the rationale for the present NRA. [this paragraph may not be needed]

To understand the direct radiative impact of aerosols on climate, measurements are needed of the variation of the spatial (horizontal and vertical) distribution of aerosol, expressed by the optical thickness or mass concentration. Also required is knowledge of aerosol absorption, scattering, size distributions and compositions. These properties may have important diurnal variations. Frequent global measurements of the variation of the aerosol spatial distribution and some key properties are only achievable by Earth observations from space.

The atmospheric physics panel under the EOS post-2002 process have separated the measurements to address the first science question by focusing primarily on direct radiative forcing and the second science question to focus on cloud radiation feedback processes, as well as aerosol indirect radiative forcing. This approach has been taken in order to most efficiently limit the number of measurements to be made from a single space platform.

Aerosol Radiative Forcing Research Mission

The first priority for the discipline is therefore a one-time (~ 5 year duration) experimental or discovery mission to characterize aerosol distribution within a sufficient number of independent atmospheric columns (nevertheless a relatively discrete sample of the whole atmosphere) with sufficient vertical resolution (~ 250-500m) to deduce the aerosol origin and therefore likely composition. The mission would be launched in polar sun-synchronous orbit or a drifting inclined orbit (TRMM orbit) to sample different solar illumination conditions. The core payload would include:

- DIAL Lidar (H2O): *vertical distribution of water vapor and aerosol backscatter Heritage: LITE, LASE.*
- Multi-angle, Multi-spectral, Radiometer/Polarimeter: *As the A-band, this instrument works in synergy with the lidar back scattering profile of aerosols. Derives estimate of aerosol particle size, optical depth and single scattering albedo which is independent of the A-band retrieval. Heritage: POLDER, MISR.*

- Nadir viewing Oxygen A-band High Resolution Spectrometer: *When combined with lidar provides aerosol visible optical depth and single scatter albedo and asymmetry parameter. Heritage: MERIS*

- Broadband Solar and Thermal Infrared Radiometer: *Provides highly accurate SW and LW top of atmosphere fluxes (1% or better calibration) to act as an integral constraint on deriving radiative flux profiles. Heritage: CERES.*

2. Second Science Question: Radiation Feedback in Climate by Clouds

Radiation transfer is the primary process that determines the Earth's climate as well as its sensitivity to anthropogenic and external forcing. This transfer is principally governed by water in three physical forms: atmospheric water vapor, liquid clouds, and ice clouds. General circulation models, climate models, and cloud process-resolving models are progressing toward ever more detailed explicit formulation of cloud and aerosol microphysical/macrophysical properties and their impact on radiative fluxes. However, global data are sorely needed to validate the simplified physics represented in these models against observation.

Due to the large time and space variability of atmospheric water and clouds, and the non-linear relationship between these factors and radiative fluxes, it is not legitimate to relate global statistics of cloud and water vapor with equally broad scale estimates of radiative fluxes: *simultaneous observations* in essentially the same column of air are needed. By *simultaneous* is meant within a few minutes and within 1 to 2 kilometers. These observations are needed over a sufficient sample to accurately characterize the diversity of cloud and meteorological conditions found in the atmospheric circulation. In the simplest terms, the cloud feedback loop involves three processes:

1. *Atmospheric State determine Cloud Properties*,
2. *Cloud Properties determine Diabatic Heat Fluxes and Moisture Fluxes*
3. *Heat and Moisture Fluxes modify the Atmospheric State.*

Neither of processes 1 or 2 is known to within an order of magnitude of the accuracy needed to predict future global change. In many cases even the sign of a feedback is unknown. We briefly summarize the existing observational challenges to resolving these feedback loops, and then suggest how most of these challenges can be overcome with a combination of new and existing space-based instruments. Because clouds are at the heart of both the energy cycle and the hydrological cycle in the Earth System, they represent the most important but also the most difficult observational challenge.

Global Atmospheric State estimates for temperature and humidity profiles should improve significantly with the 4-D assimilation of AIRS/AMSU/HSB data on the EOS-PM spacecraft, as well as the later equivalent capability being designed for NPOESS. Major remaining observational problems pertinent to the cloud modeling problem are expected to be:

- Vertical velocities (convergence/divergence)
- Profiles of cloud and ice condensation nuclei (related to aerosol loading and composition)
- Temperature inversions and boundary layer depth measurements
- Very high vertical resolution water vapor measurements

For *Cloud Properties*, TRMM, EOS-AM, EOS-PM, and ADEOS will greatly improve our understanding of clear-sky and single layer cloud systems, especially for water clouds. But there will be several cloud properties which are expected to be highly uncertain with currently planned and existing space-based cloud data:

- Cloud Ice Water Path (factor of 5 to 10 uncertainty for thick ice clouds)
- Ice Cloud Particle Size (factor of 2 to 5 uncertainty especially for thick ice clouds)
- Cloud Ice Particle Scattering Asymmetry Parameter (factor of 2 uncertainty in conversion of ice cloud optical depth to cloud albedo for thin to moderately thick ice clouds)
- Cloud Thickness and Cloud Base Altitude (factor of 2 uncertainty)
- All Multi-layered cloud properties (roughly half of all cloud cases)
- Cloud vertical aspect ratio and its effect on cloud albedo

As concerns *Heat and Moisture Fluxes*, TRMM and EOS-AM/PM will greatly advance the state of the art. Several heat and moisture fluxes , however, will remain highly uncertain:

- Broadband downward LW flux at the surface for all multi-layered cloud cases (roughly half of all clouds: regional uncertainties up to 20 W/m^2)
- Broadband LW heating rates within the atmosphere for all multi-layered cloud cases (roughly half of all clouds: zonal mean uncertainties up to 25% in the LW heating rate)
- The effect of the unknown cloud properties listed above on cloud shortwave (SW) albedo.
- Global precipitation and therefore latent heat fluxes
- Sensible heat fluxes (high latitudes and winter mid latitudes)

Cloud/Radiation Feedback Research Mission

The second priority for the discipline is a one-time (duration ~ 5 years) experimental or discovery mission to measure atmospheric profiles of cloud and aerosol physical properties, optical properties, as well as latent and radiative fluxes as a function of local atmospheric conditions and weather systems. These vertical profiles will be primarily along the ground-track of the satellite, with a few of the instruments providing the larger scale context of the cloud and/or aerosol field within 100 km of the ground track. The nominal 5-year mission in either sun-synchronous or high inclination precessing orbit in order to allow sufficient sampling of poorly understood and measured polar cloud systems. Over a 5-year mission, roughly 800,000 independent cloud systems would be sampled. As proposed, there is a substantial benefit in flying this mission in formation with a precipitation mission which would provide the cloud radar and TMI-class passive microwave data, and/or with an EOS-PM type mission which would provide IR Spectrometer, broadband radiometer, cloud imager, and TMI-class passive microwave. An alternative to the EOS-PM type mission would be the NOAA N' mission. This mission could also fly in formation with the Aerosol Radiative Forcing mission.

The key measurements would include:

- Dual Polarization Backscatter Lidar : *aerosol and cloud overlap profiles for optical depths less than about 5, cloud particle phase, boundary layer depth). Ultimately a water vapor DIAL lidar can add high vertical resolution water vapor profiles. Heritage: LITE, GLAS, LASE,*

- Dual Frequency Cloud Profiling Radar (94, 14 GHz): *cloud layering for optical depths > 5, rainfall, latent heat. Heritage: TRMM 14 GHz, aircraft and surface 94 GHz radar, CloudSat)*

- Passive Microwave (low frequency): *Cloud Liquid Water Path, precipitable water vapor, surface wind speed, and assist cloud radar for precipitation. 19, 23, 37, and 85 GHz. Heritage: TMI, SSMI, AMSR.*

- Sub-millimeter Microwave or Far-Infrared Radiometer: *cloud Ice Water Path and particle size for thick ice clouds (optical depths > 5). Heritage: MLS, Airborne Cloud Ice Radiometer. Requires passive microwave water vapor channel observations such as those on MHS.*

- Nadir viewing Thermal Infrared Spectrometer/Sounder: *Ice water path and particle size for optical depths < 5 when combined with lidar cloud height. Heritage: IRIS, AIRS.*

- Nadir viewing Oxygen A-band High Resolution Spectrometer: *When combined with lidar provides ice aerosol visible optical depth and single scatter albedo, ice particle asymmetry parameter, and effect of cloud aspect ratio on scattering photon path length distribution. Heritage: MERIS.*

- Multi-angle, Multi-spectral, Radiometer/Polarimeter: *As with the A-band, this instrument works in synergy with the lidar back scattering profile of aerosols and clouds. Derives aerosol particle size estimate, as well as aerosol optical depth and single scatter albedo which is* *independent of the A-band retrieval. Also may have ability to provide some ice particle habit information. Heritage: POLDER, EOSP, MISR.*

- Broadband Solar and Thermal Infrared Radiometer: *Provides highly accurate SW and LW top of atmosphere fluxes (1% or better calibration) to act as an integral constraint on deriving radiative flux profiles. Works in synergy with lidar/radar cloud layering data for LW radiative flux profiles from surface to TOA. Using two broadband channels in the solar split at 0.7 µm, then provides 1% calibration for visible cloud optical depth. If contains both broadband LW and 8-12 µm window, then also provides calibration standard for infrared window spectral channels and cloud emissivity. Heritage: CERES.*

- Simple Visible Infrared Imager: *Provides cloud field context: cloud fraction, optical depth, and cloud temperature for a 500 km swath. Horizontal cloud optical depth field allows matching of any differing sized radiometer fields of view at nadir. Minimum capability is 500m spatial resolution for two spectral bands: visible and infrared window.*

3. Third Science Question: Variability & Trends in Basic Climate Variables

<u>Aerological Variables</u>

The principal "greenhouse gas" which moderates the amount of longwave radiation transfer to space is water vapor. While reasonably accurate climatological information on the distribution of water vapor in the lower layers of the troposphere exist over land (balloon sonde hygrometry), current knowledge is much more sketchy for the upper troposphere and the full troposphere over the ocean.

The distribution of water vapor in the troposphere is highly variable in space (coherence length ~ 50 km) and time (time constant ~ 1 hour), and generally strongly dependent upon mesoscale weather events such as fronts and convective cells. For this reason, no single measuring technique can serve to characterize the distribution of this essential atmospheric constituent on all relevant time- and space scales. The most precise and complete remote sensing information has been obtained by a combination of IR and microwave spectrometer/radiometers that constitute "atmospheric sounder systems" on meteorological satellites. The latest and most advanced entry in this domain is the AIRS + AMSU sounding system on EOS PM-1.

Precision temperature and moisture sounding is essential to the study and prediction of the global water cycle, its variability and its response to climate change. Current General Circulation Models (GCMs) have a rather poor representation of the hydrological cycle. As an example, many GCMs treat moist convection by parameterization schemes that describe the average effects of a large number of small-scale convection events. These schemes have been shown to produce very different temperature lapse rates, water vapor distributions and climate feedbacks. Current GCMs are not yet capable of providing accurate description of the transport of the water cycle such as the variability of the recycling rate of the hydrological cycle or the trends and variations in the upper tropospheric component of the water vapor. The basic properties of many of these transport processes can be determined directly from satellite data. Thus, enhancing the quality of retrievals of global atmospheric temperature and moisture vertical structure is requisite to improving the accuracy of GCMs as well as providing information for climate research and weather applications.

Accurate temperature and moisture information are also important for studies of both short-term and long-term processes in the atmosphere. The same measurements that improve the accuracy of the fast components of the Earth system, such as forecasting of precipitation, will also improve the accuracy and usability of data assimilation products such as surface fluxes which are indispensable for understanding changes in the slower components of the Earth. Like the AIRS - AMSU - HSB instrument combination on the EOS PM-1 satellite, the next generation sounders should provide accurate measurements of the atmospheric temperature and moisture under all weather conditions and in the presence of clouds in the fields of view. The spectral resolution, radiometric accuracy and low noise-equivalent-radiance characteristics of the AIRS instrument should be maintained by the instruments chosen for the EOS post-2002 mission.

Radiation Variables

Satellite measurements of longwave and shortwave TOA radiation fluxes, as well as the derived clear sky fluxes and cloud radiative forcing, are widely used as validation checks for GCM simulations because computed TOA fluxes integrate a number of model processes and provide a convenient diagnostic check against measured quantities. These model quantities or model computations include: water vapor distribution, cloud distribution and optical properties, ice/liquid phase prescriptions, and radiation transfer in clear and cloudy atmospheres. Regional comparisons of GCM simulated and measured TOA flux quantities provides emphasis on specific regionally dependent processes.

In addition to GCM validation, satellite derived TOA radiative fluxes may be used for studies of long term trends and their relationship to other climate variables (although no such trend has been identified so far within the uncertainty of the measurement). The last CERES instrument is planned for the EOS PM-1 payload. Continued measurement of broad-band TOA radiative fluxes would require additional deployment of one or several CERES instruments to cover the period from 2006 to the first NPOESS launch. The mission should overlap EOS-PM-1 and NPOESS C1 by at least 6 months to allow intercalibration of instrument data records. An explicit discussion of the priority of this particular measurement relative to other climatological observations, for the specific purpose of detecting global climate change, remains to be presented.

(3.a) Variability & Trends in Aerological Quantities Mission

The EOS post-2002 mission envisioned will extend the high precision atmospheric temperature and water vapor record initiated with EOS PM-1, at least over the interim period after the termination of PM-1 and the launch of the first spacecraft in the operational NPOESS series. This objective is considered very important to identify any significant trend over a full 10-year period (such as drying of the upper troposphere by increased convective activity, as posited by Lindzen), to provide essential background aerological data for cloud and aerosol process studies, and characterize the weather systems in which these processes take place.

This EOS post-2002 mission designed to contribute to long-term systematic observations of basic atmospheric parameters, could be implemented by flying copies of the AIRS and AMSU-A instruments presently being built for EOS PM-1 (alternatively, an advanced version of the PM-1 microwave sounder using new microwave technology could be considered). The orbit would be polar sun-synchronous. The nominal payload would include:

- Atmospheric Infrared Sounder: *Repeat flight of the EOS AIRS instrument provides high accuracy and high spectral resolution spectro-radiometry covering nearly 2400 bands in the infrared and visible ranges: 3.7 - 15 μm and 0.4 - 1.0 μm. These ranges have been specifically selected to make the measurements of temperature and humidity, among other products.*

- Advanced Microwave Sounding Unit -A: *Repeat flight of the AMSU-A instrument provide temperature profiles from the Earth's surface to a 43-kilometer altitude, total column water vapor content, and an indication-of-rainfall using 15 channels in the frequency range of 23 to 89 GHz.*

(3.b) Advanced Technology Microwave Sounder Demonstration Mission

The development of high-performance Monolithic Microwave Integrated Circuit (MMIC) technologies for the microwave frequency domain useful for atmospheric temperature, moisture and cloud sounding has made it very attractive to combine in a single integrated unit the capabilities of existing operational sensors AMSU-A and B (or HSB). The development and flight demonstration of a prototype instrument that meets operational application needs, in addition to NASA long-term earth science objectives, could be given priority in the Enterprise's plan if supported by an active participation of the user agency for instrument development, demonstration and transition to operational use.

- Advanced Technology Microwave Sounder: *MMIC technology used in an advanced technology version of AMSU-A and B. AMSU-B (EOS HSB), is a 5 channel humidity sounder operating in the frequency range of 150 to 183 GHz. Heritage: AMSU-B, HSB.*

(3.c) Variability & Trends in TOA Radiative Fluxes Mission

Broadband Solar and Thermal Infrared Radiometer: *Repeat flight of the EOS CERES instrument provides a continued record of accurate SW and LW top of atmosphere fluxes (1% or better calibration) to act as an integral constraint on deriving radiative flux profiles. An advanced broadband instrument using two broadband channels in the solar split at 0.7 μm, would provide 1% calibration for visible cloud optical depth. Heritage: CERES.*

4. Fourth Science Question: Secular Changes in Solar Radiative Forcing

Monitoring total solar irradiance, the solar radiant flux density at the mean Earth-Sun distance, has been a science goal for more than a century. At any time in Earth's history the Earth's climate has been significantly determined by the absolute magnitude of the total solar irradiance (TSI) and the complex forcings and feedbacks found in the climate system. The first long-term solar monitoring instrument in space utilized an electrically self calibrating cavity sensor, part of the Earth Radiation Budget (ERB) experiment on the Nimbus 7 spacecraft. The ERB database, beginning in late 1978 and continuing to early 1993, is the longest currently available. Unambiguous evidence of TSI variability was first detected in the highly precise results of the Active Cavity Radiometer Irradiance Monitor (ACRIM I) experiment on NASA's Solar Maximum Mission (SMM) in 1980. The mutually corroborative function of the ACRIM I and ERB results has played an important role in verifying TSI variability on the solar activity cycle time scale.

The precision TSI climate database is currently being sustained by two experiments; namely, (1) the UARS/ACRIM II, launched in 1991 and the (2) the Differential Absolute Radiometer (DIARAD) on the European Space Agency's (ESA) Solar Heliospheric Observer (SOHO)/Variability of solar Irradiance and Gravity Oscillations (VIRGO), launched in late 1995. NASA planned TSI experiments are EOS/ACRIM (October, 1999) and the Total Solar Irradiance Mission (December, 2001). The major concern in sustaining the long term TSI database is in providing overlap between successive members of the series. Failure to provide adequate overlap between these experiments could result in a loss of relative precision in the long-term TSI database. A key objective of the post-2002 EOS missions is to provide sufficient overlap with the TSIM mission and to provide continuity with equivalent or better precision and accuracy to the measurements made previously.

The NPOESS climate workshop recently indicated the need for spectral measurements to provide solar radiation quantities more physically relevant for climate. The workshop specifically pointed out the value of spectral measurements at 200-300 nm and 1500 nm. Spectral measurements of these two wavelength bands have been incorporated in the design of the TSIM mission to be launched in December, 2001 and will continue through the time period of the post-2002 EOS missions to be considered here.
The post-2002 total solar irradiance missions will continue the precise total solar irradiance data record measured by NASA funded spaceborne instruments since 1979 until the NPOESS systems are available. NASA's interest in continuing total solar irradiance measurements is in considering the effect of this variability on the Earth's climate.

Total Solar Irradiance Monitoring Program

This program will include the planned TSIM (expected to be launched in Dec., 2002), to be followed by at least two subsequent free-flyer missions. The nominal plan is currently for NPOESS to systematically include a TSI instrument on one of its operational satellites, beginning at the end of the next decade.

- Total Solar Irradiance and Spectral Components: *Repeat flight of the TSIM payload which consists of an total solar irradiance, active cavity radiometer, and spectral instruments sensitive to 200 - 300 nm and 1600 nm. Heritage: ACRIM, TSIM.*

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

ATMOSPHERIC CHEMISTRY

Summary of Step 1 Mission Concept Reviews July 1998

RESEARCH-DRIVEN PRIORITIES FOR POST-2002 ATMOSPHERIC CHEMISTRY MISSIONS

The Leading Questions

In the last two decades an integrated program of space, aircraft, balloon, and ground-based measurements has established that the chemical composition of the atmosphere is changing and that some of the changes, such as the buildup of chlorofluorocarbons (CFCs) and of carbon dioxide are the result of human activities. In the case of CFCs and other halogen containing substances, it has been further established that such long-lived compounds are lifted into the stratosphere, broken down by solar ultraviolet radiation, and become the sources of highly reactive chlorine and bromine atoms, which catalytically deplete the earth's protective layer of stratospheric ozone.

In response to these findings, the nations of the world have placed limits on the emissions of halogen-containing chemicals whose concentrations are now beginning to decrease in the lower atmosphere. Within the next decade they will decrease in the stratosphere, which will result in less depletion of stratospheric ozone. A major challenge of atmospheric chemical research in the coming decade is to follow this process and to ensure that no unexpected problems with stratospheric ozone arise from the CFC substitutes and growing use of other halogen compounds or from climate changes traceable to human activities that could affect stratospheric chemistry.

Buildup of stable, long-lived gases such as carbon dioxide, methane, and nitrous oxide underlies the "greenhouse gas" phenomenon and is a forcing factor in radiation balance. More reactive gases, such as carbon monoxide and ozone, also play an important role in this phenomenon. Understanding the chemistry of these gases, most of which occurs in the troposphere, is another major focus of global atmospheric chemistry research.

Apart from the role of these reactive gases in global radiation balance, there is another important issue surrounding them. As the developing and emerging nations, particularly in Asia and Latin America, grow in population and economic activity, emissions of pollutant gases, such as CO and the oxides of nitrogen that largely control tropospheric ozone, will undoubtedly increase enormously. The effects of this growing atmospheric pollution on a global scale are not well predicted because natural processes that both emit gases into the atmosphere and remove human pollutants through photochemistry are not well characterized. Understanding and predicting these effects will be a frontier area of atmospheric research for the next decade and beyond. It is a global scale problem that lends itself particularly well to the use of space observations and correlative and complementary *in situ* measurements

Given the current status of knowledge of stratospheric and tropospheric chemistry and expected scientific return from current and planned space measurements (UARS, TOMS, SAGE, and the instruments on the planned CHEM satellite), a series of measurements with smaller instruments that will incorporate advanced technology can be identified for the post CHEM era with the new NASA paradigm of smaller, focused missions.
For stratospheric chemistry global measurements of total ozone and ozone vertical distributions will be the principal long-term requirement as the ozone layer recovers in response to the Montreal Protocol limitations on halogen-containing chemicals. To track cause and effect, measurements will be needed of several key chemical species that are involved in the chemistry of ozone depletion or that are chemical tracers of atmospheric transport. Measurements of the aerosol content of the stratosphere will define volcanic influences on stratospheric chemistry. Direct measurements of source gases such as CFCs, hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) will also be a long term need.

For tropospheric chemistry global scale measurements of ozone as a function of altitude are key requirements from both a climate impact and a global pollution perspective. The ozone concentration levels in the troposphere are controlled to a large extent by concentrations of oxides of nitrogen which originate mostly in the lower troposphere. Long term measurements oxides of nitrogen will be needed to track cause and effect relationships between tropospheric ozone and pollution growth. Measurements of carbon monoxide concentrations as a function of altitude and geographic location will be valuable as a pollution indicator and a tracer for tropical overturning. Natural fluxes of key tropospheric chemicals into the atmosphere from both land and water will be a key input to global chemical models. It will also be important to determine the extent to which changing atmospheric aerosol concentrations will modify tropospheric chemistry.

Can we understand and predict how atmospheric composition is changing?

The studies undertaken to achieve this general scientific objective will answer three specific questions that are certain to be at the center of public environmental concerns regarding the changing chemical composition of the earth atmosphere during the first few decades of the next century:

- *Is the Montreal Protocol working as expected to stop ozone depletion in the stratosphere by manmade chemicals, and are there any threats not yet recognized that require additional attention and action ?*

- *How can space observations contribute to better detection and characterization of regional to super-regional air pollution and assist in dealing with control issues that transcend state and even national borders?*

- *To what extent is industrial and urban pollution distributed globally and what will be the global atmospheric consequences of large-scale pollution as emerging economies greatly increase their use of fossil fuels?*

1. Stratospheric Chemistry Mission

Background

Following the measurements of UARS and CHEM the RFI panel recommends that future stratospheric chemistry measurements should focus on (1) the anticipated recovery of the ozone layer following the projected decreases in anthropogenic halogen (chlorine and bromine) and (2) climate feedbacks associated with the changes on upper tropospheric and lower stratospheric ozone and water vapor.

Science Questions

(1) How is ozone changing as anthropogenic halogen levels decrease? What is the change in the concentrations of trace gases and aerosols in the stratosphere? What are the possible feedback mechanisms connecting ozone depletion and climate change?

Measurement Requirements: stratospheric ozone, temperature, aerosols/polar stratospheric clouds (PSCs), water vapor, dominant species in the Cl_y, Br_y, and NO_y families, CH_4, N_2O, HF, and spectrally resolved UV in the 200-400 nm region. There are three basic stratospheric latitude regions which are relatively well-mixed - the tropics, mid-latitudes, and polar regions. The unequivocal detection of stratospheric recovery will require measurements over a long period of time (for at least 10 years starting in 2006) at high vertical resolution in each of these regions.

(2) What are the changes in upper tropospheric/lower stratospheric water vapor, temperature and ozone in response to greenhouse gas increases and decreasing concentrations in ozone depleting substances?

Measurement Requirements: Ozone, temperature, and water vapor in the lower stratosphere and upper troposphere at 1-2 km vertical resolution in the presence of clouds and aerosols.

Mission Concept

To meet the requirement of ***systematic measurement*** of stratospheric trace gases, the highest scientific priority is the development of a 10 year data record which builds on the measurements made by SAGE I, II, III, ATMOS, as well as UARS, ENVISAT, and CHEM instruments. To meet the 10 year continuity requirement, we propose an observing system comprised of an Attached Payload a long-duration platform (the International Space Station) and a series of overlapping, shorter-duration (~4 year) free-flyer missions.

Fulfillment of the measurement requirements listed above suggests a mission that utilizes occultation instruments on two spacecraft, one in polar sun-synchronous orbit and one in mid-inclination orbit. The advantage of occultation measurements is their self-calibration and high vertical resolution. The mid-inclination instruments measure mid-latitude and tropical trace gases and aerosols, while the polar platform makes measurements at high latitudes. The core instruments envisioned are visible/near infrared radiometer and IR Fourier Transform Spectrometer (FTS) systems. The mid-inclination system should continue the current plan to attach a SAGE III instrument to the International Space Station (ISS). We recommend that the SAGE instrument be accompanied by an ATMOS-type system for monitoring the additional trace gases discussed above. One of the advantages of flying on the ISS is that it provides a long-duration platform and the opportunity for instrument replacement.

The polar spacecraft would have the same core measurement objectives. However, we suggest that visible occultation measurements of stars could provide additional profiles, especially during polar night. Because of orbital geometry, the FTS-IR occultation system would have reduced spatial coverage in the polar orbit. Thus, an emission system with high vertical and horizontal resolution might be considered as an alternative. An emission system would provide a greatly augmented capability of measuring radicals and other trace gases globally. Such an emission system needs to have demonstrated long-term calibration. The emission system must also provide the required upper tropospheric and lower stratospheric water vapor and ozone measurements in the presence of clouds to meet the second science objective. If the emission instrument cannot provide the demonstrated long-term calibration or measurement suite, then a copy of the selected ISS FTS-IR instrument should also be flown aboard the polar orbiter.

Either the ISS or the polar mission should include an instrument capable of monitoring spectrally resolved solar UV irradiance. Because of the less contaminated environment around the polar orbiter and the sensitivity of short wavelength observations to contamination, we expect that such an instrument would be better attached to the polar platform. We also emphasize the importance of the mid-inclination ozone and aerosol observations. Should it become clear that the ISS cannot provide the needed platform for these observations, then an alternative scenario for deployment of mid-inclination occultation-based ozone/aerosol observations in the visible/near IR must be developed.

Mission Summary

Mid-Inclination (51.5 degrees, ISS, 2002-2010)

Visible/near IR solar occultation instrument on the ISS (begins in 2002 with a SAGE III instrument). Implementation if the IR solar occultation FTS instrument is required to become operational after the completion of the EOS-CHEM mission.

Polar Sun-Synchronous (~2006-)

Visible/near IR solar/stellar occultation instrument
Emission spectrometry instrument for ozone, water vapor, trace constituents in upper troposphere and lower stratosphere.
Solar UV Spectral Irradiance (~200 - 400 nm) measurement.
IR solar occultation FTS instrument (if needed)

2. Tropospheric Chemistry Mission(s)

Background

Ozone is one of the most important gas phase minor constituents of the troposphere. Its importance stems from three principal roles:

1) as a greenhouse gas it plays a major part in radiative forcing
2) ozone is a key oxidant in tropospheric photochemistry. Ozone photolysis is one of the principal sources of OH, which is the most important radical intermediate in the photochemical degradation of anthropogenic and biogenic hydrocarbons
3) as a photooxidant, ozone is responsible for acute and chronic health problems in humans and contributes to the long-term destruction of plant and animal populations.

Science Questions

The key science questions for a proposed tropospheric chemistry mission in the post-first series time frame include the following:

1) What is the distribution of ozone in the global troposphere? Ozone distributions are affected by the distribution of precursor gases, solar radiation, and by transport processes. Existing sonde and aircraft data are exceedingly sparse. Measurements show a high degree of vertical stratification. Vertical distributions of tropospheric ozone are strongly affected by transport from the stratosphere, regional sources such as biomass burning, urban and regional pollution, and atmospheric circulation on scales ranging from hundreds of meters (vertically) to hundreds of kilometers (horizontally).

2) What are the spatial and temporal distributions of the key precursor species for the photochemical formation and destruction of ozone? These include nitrogen oxides (NO_x = NO + NO_2), CH_4, and nonmethane hydrocarbons, including higher alkanes and olefins of both biogenic and anthropogenic origin. Like ozone, NO_x has both stratospheric and tropospheric sources, whereas hydrocarbons are produced exclusively in the troposphere. Both precursor families are subject to the same transport processes which cause the high degree of spatial heterogeneity as observed with ozone but are much more difficult (in general) to measure from space.

Mission Concept

This mission is envisioned as a process study, rather than a long-term systematic measurement challenge. The CHEM satellite will provide the first global data set on distribution of tropospheric ozone. The RFI panel suggests that the key remaining questions in the post CHEM time period will be process-related. Tropospheric ozone is expected to show considerable stratification and fine structure in horizontal distribution that will contain important information on the factors that control overall tropospheric ozone distribution. Resolution of this vertical and horizontal structure will require superior vertical and horizontal resolution of the measuring instrument. Such improvement is anticipated in the nest several years through the development, for example of a space based laser system that could be deployed for ozone measurements. Advances in other measurement techniques are also possible that would enable higher resolution ozone measurements from space. Development of these possibilities should be a major technological focus with the eventual goal of achieving understanding of tropospheric ozone processes, especially at higher vertical and horizontal resolution than will be possible with the CHEM payload.

The high vertical and horizontal resolution measurements of tropospheric ozone will need to be accompanied by measurements of ozone chemical precursors, tracers for atmospheric transport, and indicators that will help to trace the sources of the precursors. While high resolution would be extremely valuable for these measurements as well, it may not be achievable because of the low concentrations involved. Lower vertical resolution measurements to accompany the higher resolution ozone measurements would be very valuable in analyzing the processes involved in controlling ozone distributions.

This mission will address what will undoubtedly be a major issue in global change research related to atmospheric chemistry during the next several decades. The growth of emerging economies around the world will certainly increase the load of pollutant gases in the atmosphere. This will have major implications on the concentrations of climate forcing gases in the troposphere and on the ability of the troposphere to cleanse itself of pollution through oxidation of major pollution gases.

Measurement Requirements:

Ozone: The high degree of heterogeneity in observed ozone distribution leads to the following specifications for global measurements:

Vertical Resolution: 1-2 km
Horizontal Resolution: 100 km
Temporal Resolution: 12 hours

Precision/Accuracy: 10%/10%

NO_x (NO or NO_2):

Vertical Resolution: 5 km or better
Horizontal Resolution: 100 km or better
Temporal Resolution: 1 day
Precision/Accuracy: 10%/10% better than 50 pptv

NO_y (e.g. HNO_3):

Vertical Resolution: 5 km or better
Horizontal Resolution: 100 km or better
Temporal Resolution: 1 week or better
Precision/Accuracy: 10%/10%

Hydrocarbons other than Methane (e.g. H_2CO):

Measurement technology for hydrocarbon remote sensing from space is extremely limited. Only H_2CO (UV-visible) and possibly a few others, such as C_2H_6, C_2H_2, $(CH_3)_2CO$ (infrared) can be measured as a tropospheric column average. CO should be measured as a tracer of combustion-related sources.

Instrument Heritage

TES (thermal IR emission); TOMS, GOME (solar UV/Vis backscatter radiometry); LITE (space-based Lidar for active remote-sensing of cloud and aerosol). No heritage for active remote-sensing of chemical composition from space.

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

HYDROLOGY & MESOSCALE WEATHER

Summary of
Step 1 Mission Concept Reviews
July 1998

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS
GLOBAL WATER CYCLE, HYDROLOGY & MESOSCALE WEATHER

1. First Science Question: Global Precipitation

Global hydrology is the study of the movement and storage of water on or near the land surface, in the atmosphere, and its transport to the oceans. Some elements of the global water cycle are amenable to remote sensing. Precipitation is an especially important component of both the land surface and atmospheric water balances globally. Furthermore, over most land areas of the globe, it exerts the dominant control on the surface water balance (in particular, evapotranspiration and runoff), and indirectly, on the partitioning of net radiation into latent and sensible heat at the land surface. Precipitation is intimately linked with small-scale weather systems and orography, or even micro-scale processes in rain clouds. Consequently, rainfall is highly variable in time and space. At the land surface, the space-time variability of precipitation interacts with land surface characteristics (topography, soil properties, and vegetation) to determine the nature of the runoff response, i.e., partitioning of precipitation into infiltration and runoff.

Precipitation is especially difficult to measure either at the surface (e.g., from gage networks or surface radar) or from space. In situ networks are inevitably coarse relative to the scales of precipitation variability, and estimation of precipitation from surface radar is complicated by terrain blockage, ground clutter, range dependencies of the transformations from radar reflectivities to precipitation rates, and other technical factors. On the other hand, remote sensing of precipitation from space is effectively a diagnostic of the distribution of large ice particles or water drops within clouds (in the case of active or passive microwave sensors) or cloud top temperature (in the case of infrared sensors). Therefore, remote sensing cannot provide a direct estimate of rainfall reaching the ground. Nonetheless, early results from TRMM confirm that spaceborne radar can provide reliable estimates of surface precipitation rates. In fact, because the TRMM radar is able to resolve the vertical structure of water and ice particle sizes, it is being used on an experimental basis for calibration of surface precipitation radar.

In consideration of the fact that precipitation is the primary driver of land surface hydrological processes, as well as a controlling input to the fresh water balance of the ocean, the Step 1 Review Panel placed its highest priority on acquiring *hydrologically useful* measurements of global precipitation for a representative period of at least 5 years. The interpretation of *hydrologically useful* is to be sub-diurnal temporal resolution, and spatial resolution of the order of the decorrelation distance for intense precipitation events (arguably ~10 km as a compromise between convective and stratiform precipitation).

Global Precipitation Measurement Program

While the long-term objective is really to acquire a continuous record through *systematic global measurement* of precipitating clouds, it was agreed that a single 5-year intensive measurement period during the next decade would constitute a major step forward in promoting continent and global-scale hydrological research, and providing a quantitative basis for global water cycle studies. The value of the mission for surface hydrology would be particularly high in those areas of the globe most deficient in surface observations – notably Africa, South America, and much of Asia.

The mission would require launching a constellation of at least 5 satellites in staged orbits carrying:

〈 a multi-frequency, dual polarization μwave radiometer of performance comparable to TMI on the Tropical Rain Measuring Mission or ASMR on PM-1 and,

〈 A narrow-swath precipitation imaging radar (ideally two-frequency 14 GHz and 35 or 95 Ghz) on one of the 5 satellites.

The deployment of a constellation of satellites in low Earth orbit was judged to be the most promising approach achievable with the current state of the art. Consideration was given to an alternative use of sensors in geostationary orbit, possibly in combination with radiometers in low altitude orbit. It was the panel's conclusion that current (and expected, within the next decade) spatial resolution limitations would preclude this option. I meeting the scientific requirements of the mission. It was also noted that the low altitude constellation could include two already existing operational satellites in staged orbits (SSM/I microwave radiometer deployed by the DMSP)

2. Second Science Question: Space-Time Variability of Soil Moisture and Its Impact on Climate

Soil moisture (in the unsaturated zone, as compared to groundwater, which refers to the saturated subsurface) is the most active component of moisture storage over the land areas of the globe. It is an indicator of the state of the terrestrial hydrologic system on time scales relevant to flood forecasting, and a predictor of evapotranspiration due to its control on transpiration from vegetation (water stress) and exfiltration from bare soil. Near-surface soil moisture integrates precipitation and evaporation over periods of days to weeks and therefore introduces a significant element of memory in the atmosphere/land surface climate system. The fast recycling of water through evapotranspiration and precipitation over large continental regions causes the persistence of wet or dry anomalies during summer. Precise measurements of soil moisture can be obtained in situ but such measurements are only representative of a small area. Remote sensing, if achievable with sufficient accuracy and reliability, would provide essential wide-area coverage for macroscale hydrological studies and climatic anomaly prediction over large continental regions.

Experimental Global Soil Moisture Measuring Mission

The second priority for the discipline is therefore to develop effective remote sensing of soil moisture from space, using microwave sensors at relatively low frequencies (L-band or lower) in order to sense the ground surface under light to moderate vegetation cover. The objective of this experimental mission would be a 5-year demonstration of an advanced low-frequency dual-polarization imaging microwave radiometer in low earth orbit. A large real or synthetic aperture antenna will be essential in order to achieve a ground resolution of ~10 km, which would be compatible with the spatial resolution of the proposed global precipitation mission. Development of a suitable antenna system is the primary technological advance required for this mission.

3. Third Science Question: Mesoscale Weather Systems

Strong mesoscale weather systems (convective cells, fronts and squall lines, tropical storms and hurricanes) play a disproportionate role in rainfall production and strongly affect the hydrological cycle. Many weather and climate questions involve the most highly variable components of the Earth system - clouds, water vapor, aerosols, precipitation, fires, volcanoes, chemical constituents, surface temperature, among others. Observational systems, such as geosynchronous satellites, that fully observe these processes with fine time resolution can address many fundamental science questions that are difficult or impossible to answer from observations at a time resolution of once or twice per day as provided by low earth orbit satellites, notwithstanding their higher spatial resolution.

Improving the knowledge of mesoscale weather systems dynamics and thermodynamics is an important scientific goal for climate research, and a primary objective for applied weather research (e.g., US Weather Research Program) and operational weather forecasting. Because of the short time-scales that characterize the development of weather systems, observations must be conducted from geostationary orbit in order to achieve high sampling rates. The overall science goal in this area is to improve the understanding of physical, chemical and dynamical processes in the Earth's atmosphere and at the planet's surface. The more specific goals are to:

1) Advance our understanding of rapidly evolving phenomena and diurnal processes in the Earth's atmosphere and at the planet's surface.

2) Understand the role of the above processes in global and regional energy, water and constituent cycles and their impact on climate variations.

3) Apply this knowledge to the development of advanced space instruments, missions and techniques for operational monitoring and forecasting of significant and hazardous weather.

NASA-supported sensor technology developments could yield considerable improvement in the ability of operational environmental observing programs to characterize mesoscale weather and weather forecasting. The development and flight demonstration of prototype instruments that meet operational application needs, in addition to NASA long-term earth science objectives, could be given priority in the Enterprise's plan if supported by an active participation of the user agency in the instrument development, demonstration and transition to operational use. The currently known projects that are relevant to the domain of mesoscale weather include the following:

(3.a) Advanced Geostationary Sounder Demonstration Mission

Advances in IR detector array technology and long-life mechanical cooling system has made it possible to envisage the development of an absolutely calibrated, imaging Fourier Transform Spectrometer that could provide high vertical and horizontal resolution atmospheric soundings from geostationary orbit.

(3.b) Geostationary Lightning Imager Demonstration Mission

The technique for selective imaging of intra-cloud and cloud-to-ground lightnings has been successfully demonstrated by the Lightning Imaging Sensor on TRMM. A similar technique could be applied from geostationary orbit to provide continuous coverage of a large fraction of the visible earth disc and measurements of lightning strike rates in individual storms systems. It has been shown that the strike rate in a particular convective cell is closely related to the vertical velocity of the core, the formation of large ice particles and, ultimately, the rainfall rate. Thus, a geostationary lightning imaging system could provide important supporting information to estimate convective rain over the whole or part of the western hemisphere.

(3.c) Tropospheric Wind Sounder Demonstration Mission

Direct measurement of tropospheric wind (from Doppler shift measurement in lidar backscatter signal from aerosols and/or air molecules) would bring a major improvement in our ability to observe divergent motions in the atmospheric flow as well as rapid mesoscale weather development. The purpose of the mission, following the Shuttle flight demonstration of one of the two possible Doppler lidar systems (SPARCLE), is to demonstrate the operation of a tropospheric wind-finding Doppler lidar system in space over a meaningful time period (3 years or more).

4. Fourth Science Question: Surface Water Flow and Storage

River discharge is one of the three primary elements of the land surface hydrological cycle, and the primary mechanism by which fresh water moves from the land surface to the oceans. Although many river basins are instrumented to provide reliable daily (or better) river discharge data, such information is lacking for a large fraction of the world's river basins, including many of the world's largest rivers (either because discharge measurements are lacking altogether or because they are not made available to the scientific community). Development of a comprehensive global river discharge network by precision altimetry measurements of river stage from space would constitute a major improvement of spatial homogeneity of basic hydrologic data worldwide and would facilitate global modeling of surface hydrological processes.

Experimental Surface Water Measuring Mission

The third priority identified by the discipline is to observe the stage (hence discharge) of major rivers and storage volumes in lakes and wetlands, by precision altimetry. It is anticipated that roughly 5-10,000 locations globally would be identified with sufficient open water widths (> 300-500 m) to facilitate altimetric measurements. All-weather capability would be essential to achieve an overpass repeat objective of less than one week (roughly the hydrologic response time of the smallest rivers that could be effectively observed). The all-weather requirement dictates the use of radar (vs. lidar) systems. Depending on the type of sensor selected, the proposed surface water mission might be compatible with the Icesat/GLAS follow-on mission. However, a second unique requirement is the need for relatively frequent observations (revisit interval < 7 days) at the same locations. This probably would require that the instrument be pointable.

5. Fifth Science Question: Land Surface Cold Hydrological Processes

Cold climate processes (snow accumulation and soil freeze-thaw cycle) strongly affect the short term dynamics of hydrologic phenomena at the scale of river basins and climatic land-atmosphere feedbacks at continental scales. Outstanding science questions related to these phenomena are:

- How does the extent of snow and frozen ground affect climate?
- Could these factors be measured accurately enough to identify meaningful climatic trends?
- To what extent can snow and frozen ground information deduced from remote sensing data improve hydrologic forecasts?

Cold Hydrologic Processes Research Mission

The fourth priority for the discipline is to test the ability of active SAR imaging switchable from fine (< ~100 m) resolution to a relatively coarse spatial resolution (> ~500 m). The fine resolution would be applicable to estimation of the water equivalent of mountain snowpack over relatively small areas, while the coarse resolution would be used over large interior continental areas. At the coarse resolution, the mission objective would be to detect freezing and thawing of the ground, as well as the extent & amount of snow on the land surface (snow water equivalent). The mission would call for a dedicated satellite in polar sun-synchronous orbit, carrying a low frequency (L-band or lower) SAR with low spatial resolution (~ 1 km) but covering a large swath (~ 1000 km or more) in order to allow a short re-visit time (~ 2 days).

MISSION DESCRIPTIONS

Global Precipitation Mission

Background

Precipitation is the primary driver of the land surface hydrological system. The dynamics of precipitation, along with surface solar radiation, are the primary determinants of the partitioning of net radiation into latent and sensible heat at the land surface. Knowledge of the variability of precipitation at spatial scales of the order of the size of storm cells, and time scales of the order of the duration of storms (meaning spatial scales of order ten kilometers and time scales of order several hours) is essential in understanding the controls exerted by the land surface on weather and climate. Current numerical weather prediction models are not able to predict precipitation well, particularly the intensity of convective rainfall and its spatial distribution. Furthermore, there has not been much improvement in representing the physical mechanisms of precipitation and precipitation heating over the last decade, notwithstanding advances in computational design that have improved the spatial resolution of most models. No data set based on in situ observations exists globally that approaches the space-time resolution requirements relevant to the land surface system. From a practical standpoint, remote sensing offers the only reasonable option of developing globally coherent precipitation data sets that can be used to diagnose the performance of coupled land-atmosphere models, and to force off-line macroscale hydrological models capable of predicting and reconstructing surface moisture and energy fluxes over the land areas of the globe.

Science Questions

(1) How well do coupled land-atmosphere-ocean models and four dimensional data assimilation schemes represent physical characteristics of precipitation?

(2) What is value of diabatic heating information obtained from remotely sensed precipitation for physical initialization of numerical weather prediction models?

(3) What is value of remotely sensed precipitation for initialization of mesoscale and global scale numerical weather prediction models given inability of current models to properly distribute convection and gauge its intensity?

(4) What is value of remotely sensed precipitation for determining space-time characteristics of extreme precipitation events, and can missions of relatively short duration provide useful information about long-term changes in space-time distribution of extreme events?

Mission Summary

Objective: Obtain estimates of space-time distribution of precipitation over land areas of globe.
Resolution: 10-km spatial resolution; 3-hour temporal resolution
Mission duration: Five years.
Space system configuration: Mother satellite inclined to 65 deg. carrying a precipitation radar and passive microwave imager; 4 or more "drone satellites" on 55 deg inclined orbit or polar orbit, carrying a passive microwave imager only. SSM/I measurements from DMSP could substitute for Drone measurements.

New Technology

Radar and passive microwave radiometer technology exists; thinned array antenna for 10.7 GHz-only.

Drone radiometer requires innovation, as does meeting under 30 million cost target for individual Drone satellites.

Soil Moisture Measurement Mission

Background

Soil moisture is arguably the measurable variable that best indicates the state of the terrestrial hydrologic system. The partitioning of incident precipitation into infiltration and runoff is essentially dependent on surface soil moisture. Soil moisture at rooting depth usually controls evapotranspiration during the growing season, and indirectly the partitioning of incident solar radiation into latent and sensible heat. Therefore, it has important implication for atmospheric models, both at short-term (weather) and seasonal and inter-annual time scales (climate). Soil moisture plays a critical role in the establishment of vegetation patterns and processes, how the terrestrial hydrologic system links the physical climate system to the biogeochemical cycle. Unlike many other variables, there are no conventional alternatives to providing soil moisture measurements at regional to global spatial scales. At present, research results have demonstrated the importance of soil moisture within the physical climate system and the readiness of both the remote sensing measurement technology and retrieval algorithms.

Science Questions

Given that soil moisture measurements are available at regional to continental scales, the following science questions can be addressed:

1. Is there a feedback mechanism between soil moisture and atmospheric circulation that can be verified?

2. Do climate and weather prediction models accurately represent the land surface partitioning of precipitation into infiltration and runoff? Recent PILPS results have shown that poor parameterization of the soil moisture dynamics (infiltration, base-flow drainage and evaporation) significantly influence the partitioning of incoming radiation into sensible, latent and ground heat fluxes, and the storage of soil heat.

3. To what extent can weather prediction be improved by the assimilating soil moisture observations? And does this vary seasonally and for different global locales? Results by ECMWF (for the central portion of the US during July 1993) seems to indicate that substantial improvements are possible.

Mission Summary

Objective: Global mapping mission for soil moisture.
Resolution: 10 km.
Repeat: 3-day repeat
Orbit: Near-polar, sun synchronous (6 am/6 pm equatorial crossing time).
Duration: 5-year
Other: Compatible with a global salinity mission (instrument could retrieve ocean salinity if suitable signal/noise ratio can be realized.)

New Technology

Continued development of antenna technology will be required (to increase spatial resolution below 50 km), instruments technology existing

Advanced Geostationary Sounder Measurement Mission

Background

Because of the cost and technology limitations which existed a decade ago, EOS terminated the Geosynchronous Platform component of the EOS earth science observing program. The importance of the geostationary orbit for a research satellite is its unique ability to observe the time continuity of both surface and atmospheric phenomenon. This high time sampling rate allows monitoring of fast processes such as cloud systems, severe storms (e.g. hurricanes and severe thunderstorms), and systematic observations of the Earth’s diurnal cycles. This mission would utilize an infrared sounder for determination of temperature and humidity profiles, but would be compatible with other geostationary measurements. New technologies could include large focal plane arrays, mechanical coolers, lightweight composites, and solid state lasers. Rapid data processing systems allow high spectral resolution measurements from geostationary orbit to be developed and implemented for a reasonable cost.

Science Questions

1) Are changes occurring in rapidly evolving phenomena and diurnal processes in the Earth's atmosphere and at the planet's surface, and if so, how do those changes in “fast” processes affect long-term climate?

2) Can satellite-based observations of mesoscale weather phenomena provide useful information for mitigation of natural disasters?

Mission Concept

GeoLab is a single geostationary satellite carrying one or more spectrometers capable of achieving continuous spectral coverage between 0.5 and 15 microns with high resolving power (l/Dl = 10,000). Two general sampling scenarios are envisioned: (a) meteorological sounding using 1 cm^{-1} resolution for a 3,000 km region with a 1.5 minute dwell time, and (b) multi-spectral imaging (50 cm^{-1} resolution for a 10,000 km region with a 0.15 min. dwell time. Atmospheric chemistry measurements would also be feasible. Spatial resolution is 20 km for the first mode, and 4 km for the imaging mode (1 km at 0.5 mm). Signal to noise performance will be determined by the coverage and resolution tradeoff selected by the investigator. The geosynchronous platform is moveable in orbit so that it can be stationed over different equatorial longitudes to enable global observations. Sufficient fuel would be available (50 kg) to allow 25 changes of 90 degrees longitude over the 5 year life of the mission, with one month to accomplish each satellite change in longitude. Expected regional and seasonal study areas would include tropical biomass burning regions, ENSO events, mid-latitude severe storms, hurricanes, and the Indian monsoon.

New Technology Required

Investigation of optimal data downlink: through orbiting communication satellites or direct transmission to ground antennas. Detector arrays (Si, InGaAs, and HgCdTe) are currently available.

Tropospheric Wind Sounder Demonstration Mission

Background

Doppler wind lidar is the leading (if not only) concept for direct measurement of global scale troposphere wind fields with spatial resolution and accuracy needed to significantly impact numerical weather prediction. A mission is needed to demonstrate an intermediate, free-flyer instrument with accompanying data analysis and assimilation, which would be intermediate between SPARCLE and an operation concept.

Science Benefits

Numerical weather prediction capabilities would be improved in the following areas:

- Fluxes through Boundary layer into free troposphere
- Transport calculations, Particularly for water vapor
- Ageostrophic dynamics

Mission Concept

Global-scale measurements of horizontal wind field, with high vertical resolution throughout the troposphere and lower stratosphere, using a direct measurement technique rather than inferences from mass fields are a major need of numerical weather models. Particular needs exist in the tropics, due to scarcity of data and lack of geostrophic equilibrium and the Southern Hemisphere due primarily to scarcity of direct measurement data.

A demonstration wind lidar mission on a free-flyer, either polar orbit of high inclination orbit, will advance the instrument technology, the data analysis algorithm sophistication, and the NWP data assimilation sophistication. The mission should employ scanning optics for swath coverage of at least 500-km width, with either a continuous conical scan or “step-store” conical scans.

The measurement objectives would be to provide vertical resolution of 1 km in free troposphere, and <500m in boundary layer, with <100 km horizontal resolution. Wind measurement accuracy would be +/- m/s in lower troposphere, +/- 2-3 m/s in mid and upper troposphere. Spatial sampling strategy would address the “representatives” uncertainties in order to avoid turbulence and spatial structure as a dominant source of uncertainty. The utilization of adaptive sounding resolution and selective targeting should be encouraged.

Mission Summary

- High-Inclination orbit (≥ 60 degrees)
- Doppler wind lidar, scanning optics for ≥ 500 km swath width
- Mid-term flight (~ 2004-2005)
- Detection technique: baseline coherent detection using aerosol backscatter, but allow for potential breakthroughs using non-coherent detection and molecular Rayleigh backscatter

Surface Water Monitoring Mission

Background

River discharge is one of the three primary modes by which fluxes of moisture occur at the land surface. Although it is typically measured via in situ methods for small to moderate streams in the developed world, the discharge of many/most of the world’s major rivers is not monitored at all, and/or is not available to the scientific community in a timely manner. River discharge is an integrator, and is would be extremely useful as a diagnostic for climate and weather prediction models, were it available in near real time. Furthermore, river discharge is an important driver of ocean circulation. Also, changes in moisture stored in inland water bodies may be comparable to interannual soil moisture storage change on a global basis, and is certainly a regionally important component of the surface water balance.

Science Questions

1) Can stream discharge be observed operationally from satellite sensors?

2) Can the seasonal and interannual changes in storage of moisture at and near the land surface be documented over large river basins? Are these storage changes properly accounted for in weather and climate models, and if not, what are the implications for prediction of land-atmosphere moisture fluxes?

3) What are the implications of observed seasonal and interannual variability of freshwater fluxes on ocean circulation and salinity? Are the effects of these variations properly represented in the current generation of coupled land-ocean-atmosphere models?

4) What is the extent of the variation of seasonally inundated areas in the flood plains of the major world rivers? What are the implications of variations in the extent of inundated areas for the flux and storage of carbon and nutrients. Human health?

Mission Summary

A pointable radar altimeter would be required to determine stage (hence discharge) at ~5000 “pseudo-station” locations on major world rivers, with overpass repeat less than 7 days. The instrument would also be targeted to observe stage of ~1000 of the world’s largest lakes and other inland water bodies.

Repeat: 7 day
Orbit: 66^{o} inclination
Duration: 3-5 years
Other: vertical resolution of altimeter required ~2 cm over open water (e.g., large lakes); 5 cm over rivers; assumed footprint 300-500 m.

New Technology

Altimeter would need to be steerable, for repeat to same “pseudo-station” locations.

Land Surface Cold Processes Mission

Background

Cold season processes (snow extent, water equivalent, and soil freeze thaw status) strongly affect the short term hydrologic dynamics at river basin scales, and land-atmosphere feedbacks at continental scales. For instance, in the interior of North America and Eurasia, and in high altitude mountainous areas, much of the annual precipitation contributing to streamflow occurs as snow during the winter months. This storage strongly affects the seasonal cycle of runoff. The freeze-thaw status of the soil surface determines the relative amounts of incident snowmelt and precipitation that contribute to runoff as opposed to infiltrating, and differences in albedo between snow-covered and snow-free areas result in large contrasts in net radiation during the thaw period. Nonetheless, snow and frozen ground are not currently well measured in space and time, due to limitations in spatial resolution of passive microwave instruments, and temporal resolution and other limitations of radar.

Science Questions

1) How do the spatial extent of frozen ground and snow influence land-atmosphere feedbacks at regional and continental scales? How well are those feedbacks captured in numerical weather prediction and climate models?

2) Can the seasonal extent of frozen ground be monitored accurately enough by remote sensing to provide a useful indicator of climate change?

3) Can remote sensing provide information about the extent of snow and snow characteristics and the extent of frozen ground that could improve hydrologic forecasts used in the operation of water resource systems?

Mission Summary

Two-frequency (L-band, X band) dual polarization SAR switchable from scan (~ 1 km resolution) mode over large interior continental areas with modest relief to moderate (sub 50 m) resolution over mountainous areas, for estimation of snow extent, water equivalent, and soil freeze-thaw state.

Repeat: ~3 days
Orbit: sun-synchronous
Duration: 3-5 years

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

OCEAN & ICE

Summary of Step 1 Mission Concept Reviews July 1998

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS OCEAN & ICE

1. First Science Question - Understanding and Predicting Climate

The oceans provide thermal inertia, significant meridional heat transport, and spatially/temporally varying heat storage in the climate system. They also serve as vast potential sources and sinks of compounds critical to important biogeochemical and physical processes. The oceans are thus a fundamental component of the Earth's climate system. Interannual to multi-decadal climate prediction requires the ability to forecast the state and dynamics of the oceans. Oceanic prediction, in turn, requires continuous global observations of the oceans' dynamic, thermodynamic, and biogeochemical states (for model initialization and validation); measurements of the external forces that drive oceanic variability; and development of accurate ocean forecast models. The broad range of time and space scales associated with climate-critical ocean processes requires systematic ocean observations with high spatial resolution and global coverage over a continuous range of time scales, from hours and days (for diurnal, coastal, and mesoscale eddy processes) through decades (for basin-scale upper ocean circulation and to provide a statistically robust description of seasonal-to-interannual processes and for processes such as meridional overturning/deep water formation, secular sea-level changes, and biogeochemical cycling).

NASA and international programs/missions over the last two decades have demonstrated the ability to acquire scientifically useful measurements of sea surface height using radar altimeters, all-weather vector winds from microwave scatterometers, and cloud-free sea-surface temperature from infrared radiometers. These measurements are planned to be acquired in the first phase of EOS. The Panel noted that improved understanding and prediction of seasonal to interannual climate required systematic, consistent, simultaneous acquisition of these measurements continuously over at least a 15-20 year time period, as well as improvement in their accuracy and sampling characteristics. The Panel thus recommended (in priority order) the following measurement program in the post-2002 period to address the question of understanding and predicting climate.

(1.a) Ocean Surface Topography Program

The first priority expressed by the discipline is the continuation of systematic, accurate ocean surface altimetry measurements, following the lead of French/US TOPEX/Poseidon and Jason projects. In 1992, a group of international experts identified three critical climate issues that could be addressed scientifically using precision altimeter measurements (Koblinsky et al., 1992): determination of upper ocean circulation and associated heat transports; observation and monitoring of long-term-mean sea level change; and observation and monitoring of polar ice sheet variability. (Further discussion of polar ice sheet measurements are postponed to the second science question below.)
The capability of spaceborne radar altimeters to measure ocean topography and allow estimation of upper ocean currents has been demonstrated by the US Seasat (1978) and Geosat (1985-89) missions and the ongoing joint U.S./French TOPEX/POSEIDON mission (1992-present). Although the measurement principle is straightforward, quantitative determination of the climatically important mass and heat transports in the upper ocean requires measurement of sea-surface topography with 1 cm accuracy coupled with appropriately accurate measurements of the geoid, knowledge of open-ocean tides, and information on atmospheric surface pressure.

The global coverage of satellite altimetry makes it a powerful approach for monitoring the long term variations in sea level. (The conventional approach using tide gauges suffers from serious sampling problems and requires averaging over several decades of data to obtain a reliable sea level trend.) It has been demonstrated that systematic drifts in mean sea level measurements by satellite-borne altimeters can be reduced to the required ~1 mm/year level by supplementing the spaceborne measurements with a network of 20-30 well distributed, and well surveyed (by GPS) tide gauges.

The scientific utility of the ongoing TOPEX/POSEIDON and planned Jason-1 (to be launched in May, 2000) missions results in part from their unique emphasis on mission design (e.g. orbits chosen to minimize aliasing of tidal errors into climatically critical annual time scales) as well as the accuracy, precision, and spatial/temporal resolution of the measurements. Acquisition of the required multi-decadal, consistent data set will thus require flights of similarly well designed missions meeting the stringent science requirements on or about 2004 (Jason-2) and 2009.

(1.b) Ocean Surface Wind Program

The second highest priority of the Panel was continuation of a global, multi-decadal data set of all-weather surface vector winds over the ocean. Continuous, global, consistent, and systematic measurements of near-surface vector winds are essential for the understanding and predicting ocean circulation and air-sea exchanges of energy, momentum, and chemicals. Wind stress represents the largest single momentum source to the oceans; variable wind stresses cause horizontally divergent Ekman transports leading to vertical mass fluxes and the large scale pressure gradients that drive upper ocean currents. Spatially extensive surface vector wind measurements have been shown to increase the accuracy of atmospheric general circulation models, and they are critical to the estimation of large scale upper ocean circulation and air-sea fluxes (since fluxes are sensitive to the small-scale geometry of the sea surface, which in turn is strongly influenced by wind stress magnitude).

Numerical model studies have shown that wind forcing variations with small spatial and temporal scales can cause significant changes in large-scale, low frequency ocean circulation; in addition, the relatively rapid wind variations require similarly high resolution measurements to avoid aliasing the observations (leading to systematic errors in the characterization of low frequency, large-scale wind forcing). Thus, while the overall coverage and length of the surface vector wind measurement set is dictated by climate scales, the sampling strategy must resolve the high frequency, small-scale variations present in the true wind field. Investigations by the NOAA operational community and the oceanographic research community indicate that multiple, broad-swath spaceborne vector wind instruments in coordinated orbits are required to achieve the necessary sampling.

As with radar altimetry, NASA pioneered the measurement of all-weather surface vector winds by dual-swath Ku-band microwave scatterometry with the Seasat scatterometer in 1978 and the NSCAT instrument on the Japanese/U.S. ADEOS mission (1996-97). The ESA ERS-1 and ERS-2 missions carried single-swath, C-band scatterometers, although it has been demonstrated that the inherent accuracy of the C-band measurements is lower than for the Ku-band instruments (especially for wind direction at wind speeds below ~5 m/s). Recent theoretical and experimental work indicates that vector winds (both speed and direction) may be measured using polarimetric multi-frequency microwave radiometers. NPOESS and the US Navy are investigating the potential of spaceborne radiometers for vector wind measurement, and plans call for deployment of polarimetric radiometers in NPOESS starting in ~2009. As with altimetric sea level and active scatterometer vector wind measurements, the scientific utility of the measurements for investigation of climate issues depends critically on the accuracy of the measurements over the full range of environmental conditions (including wind speed and cloud cover). Quantitative characterization of the promising passive microwave approach over the full range of conditions has not been conducted.

Prior to 2003, NASA plans to establish a global, accurate, high spatial resolution surface vector wind measurement set with the flights of the SeaWinds scatterometer instruments on the QuikSAT spacecraft (launch 11/98) and ADEOS-2 (launch mid-late 2000) missions. ESA and EUMETSAT plan to fly a dual-swath, C-band scatterometer on their future polar-orbiting METOP environmental satellite system beginning in the middle of the next decade. Although the C-band system has lower measurement accuracy than the NASA Ku-band scatterometers, the joint flight of dual-swath C- and Ku-band instruments could provide the required frequent, extensive sampling. The Panel thus recommends the flight of follow-on, broad-swath, Ku-band scatterometer instruments for the period 2005-2010 (following the ADEOS-2 mission and bridging the gap before NPOESS) to preserve the necessary multi-decadal time series and ensure simultaneity with the altimetric measurements discussed above. The choice of active Ku-band scatterometers or passive, multi-frequency polarimetric radiometers for the continued measurement of all-weather surface vector winds for climate studies will be contingent on the quantitative accuracy demonstrated by spaceborne vector wind radiometers.

(1.c) Experimental Precision Gravity Mapping Mission

Knowledge of the geoid limits the scientific utility of altimetric measurements of sea-surface topography at shorter length scales. The EGM-96 model, considered the state-of-the-art, has an error that becomes larger than oceanographic signals at scales (half-wavelength) shorter than about 1000 km. The GRACE Pathfinder (ESSP) mission will provide precise definition of the geoid on scales down to ~300 km, as well as measuring the time-dependent components of the gravity field for oceanic, hydrologic, and geodynamic research, using satellite-satellite tracking in low Earth orbit. Nonetheless, climate studies require that the altimeter-based estimates of ocean transport have errors that are no more than 10% of the oceanic signal. Since oceanic scales down to the Rossby radius of deformation (~ 20 km) are important, even GRACE will not provide the geoid measurements that are ultimately required.

Subject to the outcome of GRACE, further refinements can be introduced by using a lidar satellite-to-satellite ranging system that could improve the accuracy of the method by a factor ~10, leading to further refinement of the shape of the geoid (allows applying altimetric observations nearer to continents and characterizing coastal currents) as well as directly detecting changes in total water column mass (equivalent to a bottom-mounted pressure gauge; allows computing the total column geostrophic flow or Sverdrup circulation). In view of the importance of this fundamental measurement, the discipline made this mission one of its top three choices for one-time experimental missions (the others being surface salinity and precise polar altimetry).

2. Second Science Question: Ice Sheet Mass Balance

The NASA Polar Research program include studies of the formation, transport and melting of sea-ice, and the mass balance of the Greenland and Antarctic ice sheets.

Sea-ice drastically modifies the optical properties of the ocean surface and absorption of radiant energy from the Sun. Sea-ice also insulates the atmosphere from the underlying ocean and drastically affects the heat flux from the ocean to the atmosphere, leading to extreme cold surface temperatures and polar-specific atmospheric circulation patterns. Last but certainly not least, the formation of sea-ice (and brine rejection), its transport under the combined influence of ocean currents and wind, and its subsequent melting is a major factor in the fresh water balance of the ocean, the formation of deep water and, ultimately, the world ocean circulation. NASA and other agencies observation programs (passive microwave imaging radiometers; active microwave scatterometers) provide on-going global-scale measurements to support the study of sea-ice processes in the context of climate research. In addition, existing and future SAR systems in orbit will continue to provide occasional but essential high-resolution image data to characterize sea-ice on process scale.

The multiplicity of processes that govern the mass balance of the polar ice sheets constitute a major research goal for the study of long-term climate change and prediction of impacts on global mean sea-level. NASA is initiating a major research program in this field, relying on occasional global mapping of ice sheet texture and topography (using spaceborne interferometric SAR observations for Canada's RADARSAT and similar future programs) and a first precision topographic mission using lidar altimetry (Icesat/GLAS).

Precision Polar Altimetry Program

Establishing the existence of significant trends in the mass balance and kinematics of the polar ice sheets is obviously a long-term systematic measurement program which does not, however, require continuous measurement. The primary objective of the program will therefore be a repeat survey of the polar ice sheets, hopefully with improved accuracy, five to ten years after the completion of the first Icesat mission. The mission would double as a demonstration of altimetric measurement of the stage of large rivers and surface water bodies over continents (see Global Water Cycle and Hydrology). The project would involve a dedicated spacecraft carrying one of two possible precision steerable altimeters: lidar altimeter (heritage: GLAS / Icesat) or a "focused beam" radio-altimeter.

3. Third Science Question: Ocean Primary Production and the Carbon Cycle

The primary production of oceanic biomass is a major factor in the global carbon cycle and a governing factor in the atmospheric CO2 balance. Although ocean primary production is considered to be in steady-state on time scales of a few years, the final sequestering of carbon by the ocean in the form of dissolved inorganic carbon and carbon rich sediments controls the long-term balance of available carbon in the earth system. Biological processes in the upper water column, specifically photosynthetic carbon fixation carried out by the microalgae, affect the near-surface equilibrium and fast exchanges of carbon with the atmosphere. The equilibrium concentration of atmospheric CO2 would be one half to one-third of the present-day levels if photosynthetic production would proceed at the optimal rate allowed by available nutrients (and 2-3 times higher if there was no photosynthesis at all).

In addition to the interactions between ocean biogeochemistry and climate, the productivity of the ocean (and especially the coastal zones) sets the fundamental limit on the amount of fish that can be harvested. Thus there is renewed interest in the complex linkage between productivity and fisheries, and on the impact of human activities in the coastal zone.

The concentration of chlorophyll in the upper ocean layer can be deduced from relatively small contrasts in ocean color. While absolute calibration of such contrast measurements carried out with different instruments may be a challenge, easily observable fast space-time variations provide valuable insight into the dynamics of primary production and the processes that control it. Such ocean color measurements will be provided more or less systematically by a number of satellite missions and operational programs, including ESA/ENVISAT, NASDA/ADEOS-2, NASA/EOS AM-1 and PM-1, and eventually NPOESS (beginning around 2009).

(3.a) Global Ocean Color Mapping Program

This program calls for a gap-filling mission to extend the global observation of ocean color at moderate spatial resolution, initiated with SeaWIFS and EOS/ AM-1 & PM-1 MODIS records. (See the "Low Resolution Land Surface Imaging and Ocean Color Mission" proposed under Land Cover and Terrestrial Ecosystems below).

(3.b) Special Event Imager Demonstration Mission

A pointable multispectral imager using a large focal plane detector array and a filter wheel (Special Event Imager) has been proposed as a desirable addition to the standard payload of the GOES satellites. In addition to numerous operational applications ranging from wildfire assessments to algal bloom monitoring, the SEI could provide invaluable information (given appropriate detector performance to achieve the required high signal-to-noise ratio) to capture coastal phenomena that require high temporal resolution.

The "Special Events Imager" as proposed would focus on areas where high temporal resolution is required to resolve the effects of the diurnal and semi-diurnal tides. The present design calls for 10-12 spectral bands with 300 m resolution. The area viewed in any image would be about 300 km x 300 km. Images of an event can be refreshed every 10 minutes allowing high temporal resolution of rapidly changing conditions. Coastal ocean applications would include oil spills, river plumes, storm flooding, hurricanes, and support of process-oriented field work. The development and flight demonstration of a prototype instrument that meets operational application needs, in addition to NASA long-term earth science objectives, could be given priority in the Enterprise's plan, if supported by an active participation of the user agency in instrument development, demonstration and transition to operational use.

4. Fourth Science Question: Sea Surface Salinity

Despite the fact that oceanographers are well aware of the importance of salinity in ocean stratification and circulation, its distribution and variability are relatively poorly known compared to temperature primarily because the measurement both in situ and from space is much more challenging than temperature measurement. Remote sensing of ocean surface salinity has been demonstrated from aircraft and recent technological improvements and modeling studies suggest that this capability can now be demonstrated from spacecraft. Measurement of surface salinity from space to the accuracy of 0.1 PSU would revolutionize our thinking about the marine hydrologic cycle. Three primary scientific objects are seen for sea surface salinity remote sensing:

1) Improving seasonal to interannual [e.g. ENSO] climate predictions: This involves the effective use of SSS data to initialize and improve the coupled climate forecast models, and to study and model the role of freshwater flux in the formation and maintenance of barrier layers and mixed layer heat budget in the tropics.

2) Improving ocean rainfall estimates and global hydrologic budgets: Precipitation over the ocean is still poorly known and relates to both the hydrologic budget and to latent heating of the overlying atmosphere. The "ocean rain gauge" concept shows considerable promise in reducing uncertainties on the surface freshwater flux on climate time scales, given SSS observations, surface velocities and adequate mixed layer modeling.

3) Monitoring large scale salinity events: This may include ice melt, major river runoff events, or monsoons. In particular, tracking interannual SSS variations in the Nordic Seas is vital to long time scale climate prediction and modeling. High latitude SSS variations influence the rate of oceanic convection and poleward heat transport. These measurements will also be the most technically challenging because of the SSS accuracy needed and relatively weaker radiometric signature at low sea temperatures.

Experimental Sea Surface Salinity Mapping Mission

This program calls for an experimental mission to demonstrate the capability to monitor sea surface salinity using L-band and S-band radiometry. Progress toward satellite systems has been hindered by the need for both large antenna aperture and low noise systems to attain the necessary SSS retrieval accuracy. Technological advancements have reached a stage of maturity that these issues can be addressed at the forefront of today's technology. The objective of the mission would be to an overall tropical ocean SSS error budget of 0.1-0.2 PSU over spatial resolution of 25-100 km with temporal resolution of 1 week to 1 month.

Conclusion: Summary Statement on Mission Priorities

The Ocean & Ice Panel clearly gave top scientific priority to the maintenance and continuity of space-based measurements of sea-surface topography, vector surface winds, and ocean color. Each of these measurements are expected eventually to "converge" with planned NPOESS measurements, although a number of significant scientific and methodological questions remain to be solved with regard to the accuracy, coverage, consistency, and utility of the planned NPOESS data (e.g. aliasing of tidal signals by altimeters in polar orbit, accuracy of passive vs. active microwave sensing of vector winds, etc.). Given NASA's EOS investment and successes in initiating the global, high quality measurement sets, and the requirement for consistent and accurate data sets spanning multiple missions (and including both research and operational missions), the Panel recommended that these convergence issues be identified and addressed urgently.

Three experimental missions were rated by the Ocean and Ice Panel as the next level of priority - the Sea Surface Salinity Mapping Mission, the Precise Polar Altimetry Mission and the Precise Gravity Mapping Mission. An Advance Ocean Color Mission was also considered by the panel at lower priority and subsequently dropped from present consideration.

One mission concept was judged by the Ocean and Ice Panel to be a high priority Applications-oriented mission - the Special Events Imager.

Altimetry Mission

Science Questions:

What is the impact of ocean circulation on climate and climate variability? In particular, how do surface currents respond to the time-varying atmospheric forcing? to radiative forcing? Are there long-term changes in sea level? in geostrophic currents? in heat storage and transport?

Mission Concept: Continuing long-term measurements over the same ground-track of the sea surface height derived from radar altimetry. The first mission would be Jason-2, which is a follow-on to the Jason-1 (launched in 2000) and TOPEX/POSEIDON (T/P) missions. This mission would cover the period 2003-2006. Beyond 2006, a free-flyer Jason-3 mission is suggested for NPOESS.

Candidate Instruments: Dual frequency radar altimeter (5.3 and 13.6 GHz) flown with a 3-frequency microwave radiometer (18.7, 23.8, and 34 GHz for Jason 1) for determination of the water vapor signal. In addition, one or more satellite tracking systems are required.

Measurement Strategy: The orbit should be the same as that of Jason: 66 degree inclination, 1336 km altitude, 10-day repeat frequency. See Fu mission concept (#16) for details.

New Technology: Reduced weight and cost. Improved knowledge of the geoid would be derived from the GRACE and GRACE follow-on missions.

Mission Type: M = long term measurements

Heritage: Seasat (1978); Geosat (1985-89); TOPEX/POSEIDON (1992-); Jason-1 (2000-); Also: ERS-2, GFO, ENVISAT (1999-)

Relevant RFI Responses: 16 (Fu), 52 (Watkins)

Scatterometry Mission

Science Questions:

#1: Can we understand and predict how ocean circulation is responding to surface wind forcing? How is ocean heat storage and transport affected by wind-mixing.

#2. Can we understand and predict how marine ecosystems respond to wind forcings (vertical mixing and upwelling)?

#3. Can we understand and predict how air-sea gas exchanges will be affected by wind forcing?

Mission Concept: Continuous observation of the vector surface winds over the global ocean to provide forcing fields for ocean circulation. Other applications include: El Niño prediction, Asian monsoon prediction, forcing of Rossby waves, gyre-fluctuations, Ekman pumping and subduction, vertical mixing and upwelling for phytoplankton productivity, storm prediction, numerical weather prediction, and wave forecasting.

Candidate Instruments: A Seawinds-class Ku-band scatterometer with 25-km spatial resolution. For a complete description refer to the Freilich (#18) mission concept.

Measurement Strategy: Sun-synchronous orbit, ~800 km altitude, 2-day repeat coverage. It is assumed that concurrent measurements of sea-surface height and sea-surface temperature will be provided by other missions. (See Freilich for details).

New Technology: Fly simultaneous multi-frequency passive microwave radiometer with incidence angles of 45 or 65 deg. to investigate the feasibility of determining vector winds from passive microwave techniques as planned for NPOESS.

Mission Type: M = long term measurements; P = process studies (if combined with observations of physical and biological properties from other missions).

Heritage: NSCAT on ADEOS-I (1996-97); Seawinds on QuickScat (1998-); Seawinds on ADEOS-II (2000-)

Relevant RFI Responses: 18 (Freilich), 34 (Liu)

Ocean Color Mission

Science Questions:

Can we understand and predict how phytoplankton biomass and productivity are changing in response to climate and environmental change?

Can we understand and predict how the ocean biological “pump” affects the carbon dioxide concentration, and the concentration of other trace gases in the troposphere?

Mission Concept: Continuing long-term measurements of phytoplankton chlorophyll derived from water-leaving radiance at the global scale.

Candidate Instruments: Follow-on SeaWiFS (as a dedicated mission) or the AGI (scaled down MODIS)

Measurement Strategy: Sun-synchronous orbit, wide-swath sensor with approx. 10 spectral bands in the visible and near infrared, 10-20 nm bandwidths, 1 km resolution, 2-day repeat coverage.

New Technology: Improved signal to noise

Mission Type: M = long term measurements; P = process studies (if observations of physical properties such as sea surface temperature and vector winds are available from other missions).

Heritage: CZCS (1978-86); SeaWiFS (1997-); MODIS (1999-)

Relevant RFI Responses:

1 (Abbott), 39 (Murphy), 79 (Yoder), 13 (Falkowksi)

Surface-Air Interface Mission [later redefined as a Surface Salinity Mission

Science Questions:

Can we understand and predict how the climate system is affected by air-sea exchanges and transport of momentum, heat, and freshwater? what feedback mechanisms exist between surface fluxes and climate?

Can we understand and predict how marine ecosystems respond to changes in the upper-ocean vertical structure brought about by air-sea fluxes of momentum, heat, and freshwater?

Can we understand and predict how atmospheric composition is affected by air-sea fluxes, in particular fluxes of carbon dioxide and other trace gases?

Mission Concept: Advanced technology required to observe simultaneously fluxes of momentum, heat, gases, and freshwater across the air-sea interface. Momentum flux is derived from the vector winds (scatterometer); surface skin and bulk temperatures are derived from the IR radiometer, and salinity from the dual-frequency passive microwave measurements. Air-sea gas exchange requires knowledge of the gas transfer coefficient which is parameterized from sea surface (skin) temperature and surface wind speed. The fluxes of momentum and freshwater affect the vertical structure of the upper ocean, which in turn affects the distribution of heat, light, and nutrients within the upper mixed layer.

Candidate Instruments: Rotating, 10-m diameter, lightweight mesh antenna flown with an active microwave scatterometer, IR radiometer, and dual-frequency (L and S band) passive microwave radiometer. See concept by Liu et al. (#34) for details.

Measurement Strategy: Sun-synchronous orbit, 600 km altitude, with 6 am/6 pm equatorial crossing times, and 3-day repeat coverage.

New Technology: 10-m mesh antenna technology developed with a 2-year Instrument Incubator Program study to be ready for a post-2002 launch.

Mission Type: P = process studies; E = exploratory.

Heritage: NSCAT and Seawinds, AMSR, AVHRR, and ESTAR.

Relevant RFI Responses: 34 (Liu); 18 (Freilich); #16 (Fu); #31 (Lagerloef)

Advanced Polar Altimetry Mission

Science Questions:

Can we understand and predict changes in ice-sheet topography, and its relationship to mass-balance changes on interannual to decadal time scales? Can we understand and predict large-scale ice dynamics, freshwater flux into the ocean, and sea-level variability, and the relationship of these to climate change? (Note: a laser altimeter would provide the additional capability to address climate and atmosphere issue pertaining to cloud structure and aerosols).

Mission Concept: The mission objective is to obtain detailed 3-dimensional profiles of the large ice sheets at intervals not exceeding 5 years. An advanced altimeter is recommended for the 2008 time frame whose configuration (laser vs. radar) will depend on the outcome of the EOS GLAS mission scheduled for launch in 2001, and planned tests of advanced radar altimeters. In addition, a SAR interferometric mission is required to retrieve freshwater flux across the ice-sheet margins, and a passive microwave mission is required to obtain ice sheet emissivities, and to continue observations of sea-ice concentration and extent. It is assumed that the SAR and passive microwave missions will be conducted during the post-2002 time frame. Furthermore, a GRACE or GRACE follow-on mission is required to remove the isostatic rebound signal from observed changes in surface topography.

Candidate Instruments: Johns Hopkins University Applied Physics Lab (JHU/APL) delay/Doppler advanced microwave radar altimeter. Or a follow-on to the Geoscience Laser Altimeter System (GLAS) developed by NASA-Goddard and the University of Texas.

Measurement Strategy: Non-sun-synchronous 183-day repeat at an altitude of 600-800 km, fixed mean perigee near the North Pole, and 94-98 deg. inclination.

New Technology: Delayed/Doppler post-processing required for the JHU/APL advanced radar altimeter, and advanced LIDAR capability required for GLAS follow-on.

Mission Type: M = long term measurements based on upcoming E = exploratory missions.

Heritage: Seasat, Geosat, TOPEX/POSEIDON for the radar altimeter; Wallops Airborne LIDAR and GLAS on the ICESAT-1 2001 mission.

Relevant RFI Responses: 42 (Raney), 57 (Zwally)

Advanced Gravity Mission

Science Questions:

Can we understand and predict how climate change is affecting the time-varying surface and deep-ocean circulation? and how changes in circulation affect the climate system?

Mission Concept:

Measurements of the time-varying gravity field for multiple applications. Time-varying ocean geoid is important for understanding deep-ocean circulation. These measurements would be a valuable complement to the ongoing and advanced altimetry missions.

Candidate Instruments: GRACE follow-on.

Measurement Strategy: Satellite-to-satellite laser tracking. Pairs of small (100-300 kg) satellites flying in a 350-500 km polar orbit.

New Technology: Use of laser interferometric system for improved accuracy (compared with K-band microwave used by GRACE mission). Possible employment of “drag-free” mode in which thrusters continually fire to keep the spacecraft centered about the accelerometer proof mass.

Mission Type: M = long term measurements.

Heritage: GRACE (ESSP Mission)

Relevant RFI Responses: 52 (Watkins)

Special Events Imager Mission (Applications Oriented)

Science Questions:

Can we understand and predict how coastal and estuarine ecosystems response to tidal forcing and natural seasonal-to-interannual variations in river discharge? Can we understand how changes in land cover and land use affect coastal and near shore ecosystems? Can we understand how pollutants or nutrients carried by rivers and by atmospheric circulation affect near shore/coastal ecosystems?

Mission Concept: Multispectral imaging system onboard a geostationary platform would provide ocean surface reflectance measurements with high temporal resolution (every 15 minutes) and 300-m spatial resolution. The imager would view a selected region of size 300 x 300 km where a "special event" is being studied or observed. Special events might include a river discharge (flood), harmful algal bloom, hurricane land-fall, oil spill, or other coastal event. There are also applications for viewing land events such as forest fires and floods.

Candidate Instruments: Special Events Imager would have 10 spectral bands in the visible and near infrared. It can achieve SeaWiFS-level signal-to-noise and SeaWiFS or MODIS algorithms can be adapted to use with this instrument.

Measurement Strategy: Sensor flown on a geostationary platform. There is a possibility to fly this sensor on the GOES N platform but the decision will need to be made in the fall of 1998.

New Technology: Improved spectral, spatial, and radiometric resolution for a geostationary imager.

Mission Type: E = exploratory/demonstration; P = process studies.

Heritage: SeaWiFS (1997-); MODIS (1999-)

Relevant RFI Responses: 4 (Brown)

Advanced Ocean Color Mission

Science Questions:

Can we understand and predict how the community structure of marine ecosystems is changing in response to climate and environmental change?

Can we understand and predict how the community structure of marine ecosystems affects the chemical composition of the atmosphere?

Mission Concept: Improved capability to differentiate functional groups of phytoplankton, and to study their photosynthetic or physiological state by observing solar-stimulated chlorophyll fluorescence. Fluorescence per unit chlorophyll is an index of physiological state. Chlorophyll will be derived from reflectance in the blue-green spectral region. Chlorophyll fluorescence will be derived from the red fluorescence peak centered at 680 nm. A signal-to-noise of order 1200 is required for wavelengths > 670 nm.

Candidate Instruments: Hyperspectral imager.

Measurement Strategy: Sun-synchronous orbit, wide-swath sensor with approx. 200 spectral bands in the visible and near infrared (345-800 nm), 2 nm bandwidths, 1 km resolution, 2-day repeat coverage.

New Technology: Improved signal to noise, higher spectral resolution, onboard data processing for compression and product derivation may be necessary. Algorithms derived from NEMO experience.

Mission Type: P = process studies

Heritage: CZCS (1978-86); SeaWiFS (1997-); MODIS (1999-). Also, COIS (Navy hyperspectral sensor onboard NEMO satellite focused on coastal studies to be launched in 2000; COIS will have 30-60 m resolution; will not provide global coverage)

Relevant RFI Responses: 1 (Abbott), 13 (Falkowksi), 79 (Yoder)

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

LAND COVER/LAND USE & TERRESTRIAL ECOSYSTEMS

Summary of Step 1 Mission Concept Reviews July 1998

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS FOR LAND-COVER/LAND-USE CHANGE AND TERRESTRIAL ECOSYSTEMS

Background

The major terms representing the anthropogenic perturbation to the carbon cycle include a major net flux to the atmosphere (ca. 1.6 GtC/yr) from land-use change in the tropics. There is also a flux of approximately the same magnitude that is attributable to net ecosystem productivity in terrrestrial temperate and boreal ecosystems. The latter flux is thought to be apportioned to a combination of regrowth of previously disturbed landscapes, carbon dioxide fertilization, and the result of nitrogen deposition. The net global flux into the oceans is calculated to be ca. 2.0 GtC/yr. In addition, there is substantial interannual variation in each of these fluxes, apparent from the interannual variability in the fraction of anthropogenic carbon that remains airborne, from satellite observations of deforestation in the tropics over the past decade, and in model simulations of the response of the biosphere to climatic factors.

Quantifying these fluxes is critical to understanding the overall response of the carbon cycle to human perturbation, and also to understanding the rate of increase in radiative forcing of the climate system, since CO_2 accounts for most of the anthropogenically-driven increase in forcings.

Understanding the carbon cycle thus provides a framework for considering three major scientific issues that can be addressed with remote sensing data:

〈 Understanding the rates and locations of land-cover change, sampled at appropriate spatial and temporal scales (“the accounting problem”).

〈 Understanding the processes associated with biological productivity (“productivity”).

〈 Understanding the rates and degree to which landscapes recover from both anthropogenic and natural disturbance (“disturbance”).

Understanding the carbon cycle is not the only important topic to understand in ecology. Perturbations to the nitrogen cycle, for example, are equally important, and interact strongly with changes in carbon because of numerous biogeochemical and physiological feedbacks. Likewise, understanding the biological sources and sinks of trace gases other than CO_2 continues to be a critical topic. The loss of biological diversity and the potential consequences of climate variability and change provide similarly critical research areas. However, each of these issues interacts with the issues raised by the carbon questions through their links to productivity, land-cover change, and the response of systems to disturbance. Therefore, understanding changes in carbon provides both a significant focus for the productive use of remotely sensed data as provided by NASA’s programs and an opportunity for the scientific community to investigate a wide variety of ecologically important topics.

First Science Question: Accounting for Land-Cover Change

Land-cover change must be measured with sufficient spatial resolution to determine accurately the amount of change, its location, some diagnosis of its cause, and with sufficient temporal resolution to address interannual variability. This requires observations with spatial resolution on the order of no more than a few tens of meters, with spectral characteristics that provide continuity with the existing Landsat observations.

The review panel recommended the following option as a high priority for repeated, systematic measurements:

Land-Cover Inventory Mission (Landsat-Next)

This science issue calls for a series of missions that would provide systematic measurements of land-cover change. The spatial resolution required would be on order 10-30m, with multispectral information in the VIS/NIR parts of the spectrum. Orbital repeat time with a single orbiter would continue to be in the 16 day range. This Landsat-class mission, with a next-generation sensor on it, including sufficient bands for atmospheric correction, would be flown with mid-morning overpass time, in the current Landsat orbit. New technology would be used to cut down on the size and complexity of the instrument and mission. Launch would be in the 2004-5 time frame, with a nominal mission life of 5 years. Documentation of changes around the globe on a seasonal basis would be the primary objective. However, it is recognized that these data would also provide an enormous amount of information for a wide variety of scientific issues, as identified above. In addition, the spectral information on vegetation physiological status would receive new attention due to the availability of seasonal time-series. The Advanced Land Imager on the EO-1 mission provides one model for an instrument design, although others may be feasible.

Second Science Question: Understanding Biological Productivity

Observations that are necessary to parameterize process models for biological productivity must be maintained globally, with relatively high temporal resolution (1-2 day repeat times). These may have lower spatial resolution than the observations above, from 250m to 1km. The combination of relatively coarse-spatial resolution but finer temporal resolution than that required for land-cover inventories provides greater strength for understanding the processes that regulate biological productivity within and between seasons. It also provides a way to investigate disturbances, such as fires, which occur on short time-scales, and which therefore can be missed entirely by missions with long repeat times.

The review panel recommended the following option also as a high priority for repeated, systematic measurements:

Ecosystem Productivity Mission

This science issue also calls for a continued sequence of measurements that provide systematic measurements of many of the important parameters that regulate biological productivity of terrestrial ecosystems. The requirements are for systematic low or moderate resolution mapping (~ 250-500m) of the global vegetation cover and phenological state, with frequent repeat observations (revisit time ~ 1-2 days) in order to capture relatively rapid changes (~ 1 week) that may occur during the growth season. Spatial resolution, revisit time, and spectral information required are anticipated to be very similar to the specifications for MODIS, but the anticipation is that the technological implementation of the sensor would be more advanced. The number of bands could be reduced somewhat from MODIS, but would still include sufficient information for atmospheric correction. Overpass time would continue to be mid-morning. Launch would be in the 2004-5 time frame, with a nominal mission life of 5 years. Ultimately, these measurements should become part of the operational suite of measurements sponsored under the future operational system (NPOESS). However, a gap-filling mission is required to bridge the time between the expected lifetimes of MODIS on EOS AM-1/PM-1 and the launch of the first NPOESS platform equipped with the new Visible and Infrared Imaging Radiometer Suite (VIIRS) under development (~ 2009). It is expected that NASA could procure an early VIIRS flight model for this purpose.

Third Science Question: Recovery from Disturbance

As noted above, the rates of disturbance of various types and especially the recovery of ecosystems to those disturbances constitute one of the major uncertainties in the terrestrial carbon budget. Observations to track both the occurrence and recovery from major disturbances (e.g. fire, insect infestations, deforestation, clear-cutting) are therefore critical to understanding the overall rates of exchange of carbon between the terrestrial surface and the atmosphere. Such observations would also have important implications for understanding the biophysical linkages between the terrestrial surface and local and regional climate.

The review panel thus recommended the following option as a high priority for a one-of-a-kind, scientific exploration mission:

Ecosystem Recovery from Disturbance Mission

The disturbance recovery mission could be flown in the 2007-9 time frame, with either one or two primary instruments. The first, which was thought to be critical, would be a lidar based on technological evolution from the VCL instrument. However, instead of the survey mission implicit in the VCL ESSP mission, this mission would be a sampler, whose targets would be areas of the terrestrial biosphere that had been subject to major disturbances. The mission goal would be to characterize the recovery of those areas in terms of above-ground biomass. The second instrument on this platform would be an imager, perhaps similar to the geostationary imager in terms of spectral coverage, that would provide information on recovery for those areas in ecosystems for which the lidar might not be especially useful, e.g. grasslands and semi-arid ecosystems.

Fourth Science Question: Instantaneous Coupling of Terrestrial Ecosystems and the Atmosphere

The ability to determine the instantaneous coupling of terrestrial processes and the atmosphere on diurnal time-scales is important because of the sensitivity of the terrestrial processes controlling productivity to changes in atmospheric conditions. Results from field campaigns such as BOREAS also demonstrate the importance of understanding this coupling to weather prediction.

An option for analysis as a one-of-a-kind scientific exploration mission was proposed:

Ecosystem-Atmosphere Diurnal Cycle Mission*:* A geostationary staring mission should be explored, possibly to be flown in the 2005-6 time frame, with a sensor optimized for NDVI-type measurements, but with spectral capability extending into the thermal IR (perhaps several channels) to ensure that information on fire occurrence and intensity could be gathered on a diurnal basis. This need not be a free-flier, but could involve the development of an instrument that could become part of the GOES series, or other geostationary platforms (e.g. private communications satellites). Nominal mission life would be approximately 5 years.

Additional Missions of Importance to Ecological Science and Applications

The RFI panel additionally discussed a category of missions and measurements, which may be characterized as being of broad interest and of potential importance to terrestrial ecology and applications. Within this discussion, several ideas arose, which might ultimately be developed for ESSP-like proposals, or for joint ventures with commercial partners.

<u>Exploratory Research Missions</u>:

There was considerable interest on the panel for OSE to consider missions that are truly exploratory in nature, i.e. that did not necessarily focus on a single, specific research topic, but that sampled the Earth in new and unique ways that might reveal previously unexpected insights. Two concepts in particular emerged from this discussion. One was the notion of flying a coarse resolution (1 km) SAR, perhaps in C or L band, with a swath sufficient to give a 1-2 day global repeat time. This would sample the Earth in a manner that was consistent with AVHRR/MODIS, and which has never been attempted with current SAR missions. Such a mission could be a free-flyer, or this could be a mode that might be incorporated in a LightSAR concept. Some scientific issues are already known to which such a mission might contribute: quantifying seasonal inundation patterns in the tropics, and freeze-thaw dynamics in the boreal zone, for example. However, the real benefit might come from fusion of the SAR data with optical data from MODIS and its descendants.

A second exploratory mission that was discussed was the possibility of flying a hyperspectral imager. It was the general consensus that there were currently many interesting possibilities for analyzing hyperspectral data from space, but that there has not yet been articulated a single scientific question for which these data would provide the major critical missing information. Since general interest remains relatively high, however, there was certainly sentiment to continue investigating opportunities for providing hyperspectral data.

Approaches to Improve Revisit Times*:*

Several responses coalesced on a potential solution to one of the major problems of remote sensing of the Earth from low Earth orbit: relatively infrequent revisit times, or alternatively, revisit times that were compromises between scientific arenas. Obviously, geostationary orbits are one way to address this problem. However, this solution introduces another level of complexity in instrument design, not to mention the cost of boosting platforms into geostationary orbit. An alternative approach for investigation is to build many replicates of relatively inexpensive instruments that have been optimized for a particular observation, for example optimized for fire detection, or Vegetation Index measurements. Copies of these optimized instruments would then be flown on as many flights of opportunity as possible, so as to ensure that observational opportunities would be maximized.

This idea could be developed in both an Instrument Incubator environment, for the instruments themselves, and then perhaps explored as a joint venture with other governments or commercial launches. There was some considerable interest in this concept from an applications perspective, since the limitations introduced by infrequent revisit times are among the problems that many commercial data providers are attempting to overcome.

Regionally Specific Missions:

Several responses suggesting optimizing missions for phenomena according to regions, e.g. optimizing a mission for detecting freeze-thaw regimes in boreal ecosystems, or optimizing a mission for fire detection and recovery in boreal forest. Without necessarily addressing these specific ideas, the panel was generally interested in the concept of optimizing missions for specific regions, given the constraint that the problems to be investigated were of broad significance.

The Importance of Being Thorough

Several responses to the RFI advocated the use of multi-angle remote sensing, ‘a la’ MISR. The panel generally thought that while such data may well be of interest and scientific importance, its critical nature was difficult to demonstrate at this time. There was a relatively strong consensus that before NASA pushed very hard to continue such multi-angle measurements from a terrestrial perspective, that the community should analyze the EOS data sets.

The panel expressed a similar thought with respect to thermal multi-spectral measurements. Such measurements were part of many responses to the RFI, but the community has not expressed a strong consensus on exactly what the scientific needs are. Experience with ASTER data should enable a much stronger case to be made, outside of the geological applications, where the utility of such data are already quite clear.

Similarly, the general issue of advocating thorough analysis of the currently planned measurements received a lot of attention. The panel was consistent in its opinion that many issues in the final planning of mission concepts, instrument and mission design, and implementation could be most efficiently addressed by ensuring that current data sets be thoroughly investigated. Part of that investigation should include an emphasis on “data fusion”, i.e. understanding the additional scientific benefits to be gained from simultaneously combining measurements from sensors having very different, but complementary capabilities, e.g. SAR’s and optical measurements.

Finally, the panel expressed its strong opinion that the ultimate scientific success of any and all of these missions concepts depended critically on the continuing support of the research and analysis program. It was viewed to be important for sponsoring campaigns and fundamental research investigations that lead to new mission concepts, that validate the data and scientific products from existing flight missions, and for exploring the scientific issues that will define the OSE programs of the future. The panel also expressed its strong opinion that the RFI process must result in additional interactions with the scientific community to ensure that there is strong scientific consensus on mission scenarios for OSE in the post-EOS era. There is considerable doubt that all the important ideas have come forward yet, and much community discussion and debate must be held on even those that have come forward.

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS

SOLID EARTH SCIENCE & NATURAL HAZARDS

Summary of Step 1 Mission Concept Reviews July 1998

SCIENCE-BASED PRIORITIES FOR POST-2002 FLIGHT MISSIONS SOLID EARTH/NATURAL HAZARDS AND APPLICATIONS PANEL

1. First Science Question: Variations in the Earth's potential fields as a measure of change on the surface and interior

The panel recommends a systematic program to observe temporal variations in Earth's potential fields, with highest priority given to the gravity field. The polar/oceans panel has also recommended continued gravity observations from space because of their unique contributions to oceanography and integrated measurement of polar ice mass. The value of gravity field measurements is well described by the National Research Council (NRC) Report 'Satellite Gravity and the Geosphere' published in 1997. A main point of this report is that the time-varying gravity field is the unique quantity which reflects mass redistribution within the earth system, including weather and climate effects, oceanic circulation, tectonics, post-glacial rebound, and other processes. The concept of using temporal gravity variations to monitor such mass redistribution has already been demonstrated for spherical harmonic (SH) components of the gravity field up to degree and order 2, using time series of geocenter variations, polar motion, length of day, and LAGEOS nodal precession rate. The Earth System Science Pathfinder mission GRACE will extend this proven capability to above SH degree 100, and provide experience in required satellite technology and data processing. The panel recommendations are for continued observations to begin near the end of the GRACE mission.

Understanding the fluid dynamo processes by which planetary and stellar magnetic fields are generated has long been recognized as one of the grand challenges of science. The Panel recommends that a continued program of observations of the magnetic field be part of the post-2002 plan, given the fundamental scientific interest in this problem, and the emerging ability to interpret the data by numerically modeling magnetic dynamo processes. Magnetic field studies are suitable for cooperative efforts with the Office of Space Science, and with international partners. A program of continued observations is recommended to follow the international magnetic missions now scheduled through 2005.

(1.a) Temporal Variation of the Gravity Field (systematic measurement)

The science goal to use gravity to monitor mass redistribution in the earth over a variety of time scales calls for *systematic measurement* of the field for an extended time period. GRACE is the prototype mission concept for this purpose, but other concepts have been developed in the past. One satellite pair, like GRACE, may be insufficient to temporally sample the variable gravity field, and a multi-satellite program may be called for, an issue that GRACE should help determine.

(1.b) Magnetic Field Mission (systematic measurement)

Planned launches of SUNSAT and Oersted in 1998, and SAC-C and CHAMP in 1999 should provide high quality magnetic field observations through 2005. All these missions are at near-polar inclinations, and roughly in the same altitude range of 4-700 km. In order to separate internal (core and crust) from external (electric current) contributions, *systematic measurement* from polar orbit, plus additional observations at a variety of inclinations and altitudes are called for. Using the technical advancements achieved for the Danish Oersted satellite (non-magnetic star camera, compact spherical fluxgate magnetometer) plus evolutionary developments, a modest cost Magnetic Mapping Package (MMP), like that being built for SAC-C, could be made available for domestic and international flights of opportunity to achieve the desired goals.

2. Second Science Question: Topography and surface change

High precision observations of topography and surface deformation from space have been demonstrated with interferometric SAR, and other techniques. These observations provide the boundary condition for Earth's interaction with the hydrosphere and biosphere, allow observation and mitigation of natural hazards, and contribute to understanding erosion, tectonics, and other process which control the evolution of the landscape. Understanding and mitigation of natural hazards such as flooding, coastal erosion, volcanoes, landslides, and earthquakes can benefit from both topography and surface deformation data having high precision and spatial resolution.

The Panel identified two components needed to address this science area. The highest priority is to observe changes in elevation, with 30-100 m. post spacing, with millimeter-level accuracy (along the line of sight), using radar interferometry. For the foreseeable future, the requirement will be for study areas of interest, rather than for systematic application to the entire globe. The second priority is to determine surface elevation ('bald earth' - below the canopy level) with 1 to 10 meter post spacing, at a vertical accuracy at the 1-2 m level. Again, for the foreseeable future, digital elevations models with this resolution and precision will be required for selected study areas, rather than the entire globe.

(2.a) Interferometric SAR surface deformation (systematic measurement)

The prototype mission concept is LightSAR. The Panel recommends that in the post-LightSAR period this should be a *systematic measurement* available for science and natural hazard studies. Technical requirements for measurement of surface deformation in the presence of vegetation include L band full polarimetry, split spectrum and water vapor radiometer for path-delay compensation, and rapid revisit capabilities. A pair of satellites flying in complementary orbital planes would provide vector components of surface deformation.

(2.b) High resolution topography (ESSP-type mission)

The Shuttle Radar Topography Mission (SRTM) will provide a near-global digital elevation model, for the first time, in a common (GPS) coordinate system. The Panel noted that data with higher resolution and accuracy than SRTM could be obtained by a number of techniques, including radar interferometry or laser altimetry. An experimental mission using laser altimetry, for example, could prove the concept and lay the groundwork for a future commercial system.

3. Third Science Question: Natural hazards and applications

The panel examined two areas which have both scientific and natural hazard importance, volcanic eruptions and severe storms. Volcano-related observations from space can contribute both to science and public safety through improved understanding of eruption processes and monitoring of eruptions, plumes, and ash deposition. Space-borne measurements will contribute to understanding geologic controls on eruption processes and recurrence intervals, trigger mechanisms of final eruptions, and thermal history of eruptions. Monitoring of post-eruptive plumes and ash deposits offer the opportunity to provide aircraft warning of plume hazards, observe damage to the surface, and predict the potential for lahars. Observations of volcanic sulphur dioxide, surface temperature change, plume ash concentration and tracking, and ash deposit mapping are called for in a volcano satellite.

The panel considered the hazard-related aspects of severe storms. There is a need for improvement in the forecast accuracy of tropical cyclones over the current 1% skill at predicting landfall of a tropical cyclone within 60 miles at 72 hours before the event. This skill is likely to be improved by combining a suite of observations from geostationary orbit, including moisture and temperature soundings, surface winds, lightning frequency, and other quantities. The panel assigned a lower priority, relative to the volcano satellite. As a candidate for an operational system, this could eventually be operated by NOAA or another agency. An advanced geostationary imager/sounder also appears in the recommendations of another panel.

(3.a) Volcano Satellite (demonstration mission)

The mission concept includes sulphur dioxide outgassing observations at the volcano, ground temperature measurements, plume sulphur dioxide and ash content and tracking, and hyperspectral mapping of ash deposits on the ground, from geostationary orbit, or, for high latitudes, Molnyia orbit. The NASA contribution could be a *demonstration mission* on a single geosynchronous satellite. A global volcano monitoring program might involve 3-4 geosynchronous satellites plus 3 satellites in Molnyia orbit, and instruments on polar orbiting satellites.

(3.b) Severe Storms Research Mission (demonstration mission)

The time-critical nature of severe storms and hazard warning requires a geosynchronous satellite. The imager instrument would require approximately 18 bands to aid in the improved determination of convective cloud and water vapor distribution. An advanced sounder for improved vertical resolution of temperature and moisture fields will be important, and a lightning sensor will serve to monitor convective activity. This concept is identical to concept (3.a) identified by the Panel on Hydrology and Mesoscale Weather.